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ORIGINAL ARTICLES.

Climatic Changes in South-East India during Early Palaeolithic Times.

By F. J. Richards, L. A. Cammiade, and M. C. Burkitt; with notes on the Petrography by S. W. Wooldridge, and on the Conclusions by P. Lake.

(PLATE X.)

HUMAN artifacts can often be very useful to the geologist. When they occur in sufficient numbers and are characteristic, prehistorians can be definite in assigning the industries to a certain culture or cultures, and they can then be utilized by the geologist in the same way as are fossils. In Europe during a part of Quaternary times Lower Palaeolithic cultures flourished. Now Quaternary times in Europe can, of course, be readily subdivided into glacial and interglacial periods, but these naturally did not occur further south. In East Africa geological evidence has been adduced to show that intense pluvial periods took the place of our European glaciations, while during the interglacial phases the African areas suffered from arid conditions. Lower Palaeolithic industries are found at certain levels in East Africa and they enable the geologist to correlate the East African and European sequences. South-East India (Madras) is also not an area where glaciations ever occurred : but, we ask, can geological evidence be adduced to demonstrate climatic changes corresponding to those found to have occurred in East Africa ? Lower Palaeolithic industries occur in great numbers in South-East India ; whereas most of them have been merely collected from the surface, and are therefore useless for the purposes of exact dating, a number of finds in situ in definite layers have been made, and as in East Africa these can be used as datum lines for correlating purposes.

The Palar Plain.

The Palar Plain covers roughly the triangular area of which the coast-line between Pulicat and Sadras is the base and Arcot the apex. The plain is dissected by the Arani (called by Foote the

Narnaveram) and Korttalaiyar rivers in the north, and the Kuvam (Cooum) and Adyar rivers in the centre, while the south-west margin is demarcated by the course of the present Palar. The beds of these rivers are almost dry, except during the rains, when the water rises in devastating floods. R. Bruce Foote examined the geology of the plain in the early 'sixties of last century, and his results appeared in the *Memoirs of the Geological Survey of India*, x, 1873. The underlying rock is gneiss, which is found some 50 feet below the surface in Madras itself and outcrops a few miles to the south (Fig. 2, F). Patches of Jurassic rocks appear here and there, and a third formation (the Cuddalore series), possibly Pliocene in age, is also suspected. The sea margin is fringed with blown sand. Laterite cappings occur on all these outcrops (C, D, E). These are intersected by broad tracts of sandy alluvium deposited by the Palar river and its tributaries (A, B). Part of the alluvial has been slightly elevated in recent geological times, and the Palar, which once flowed through the Korttalaiyar valley, has been

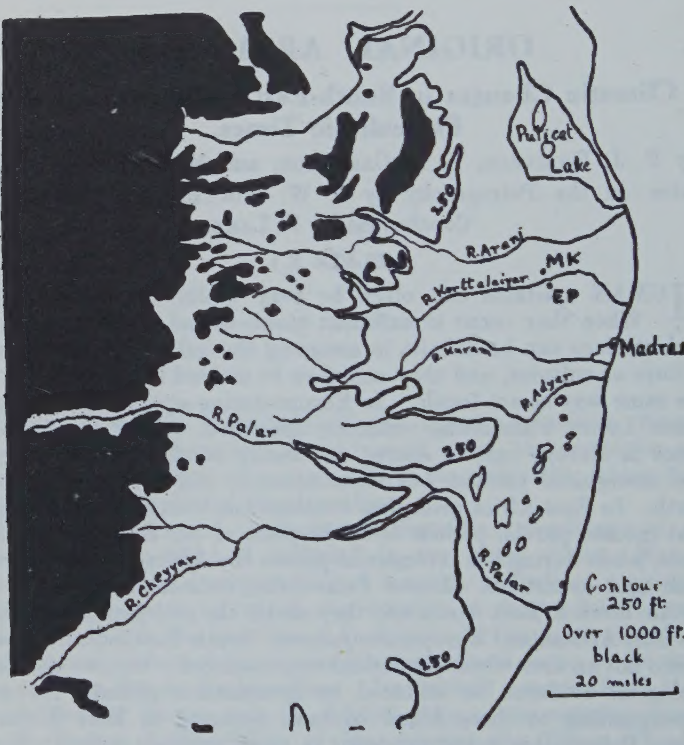

FIG 1.—The Palar Plain.

diverted into that of the Cheyyar. However, it is more particularly with the laterite that we are concerned in this paper, as large numbers of Lower Palaeolithic implements have been found embedded in it. Further, two different ages of laterite can be determined.

The origin of laterite has long been a subject of controversy.[1] The most recent theory is that laterite is formed by mineralized solutions brought to the surface by capillary action as a result of the decomposition in situ of certain kinds of rock under *certain* conditions. Probably, too, bacterial action plays a part in the process. The conditions required for its formation are :—

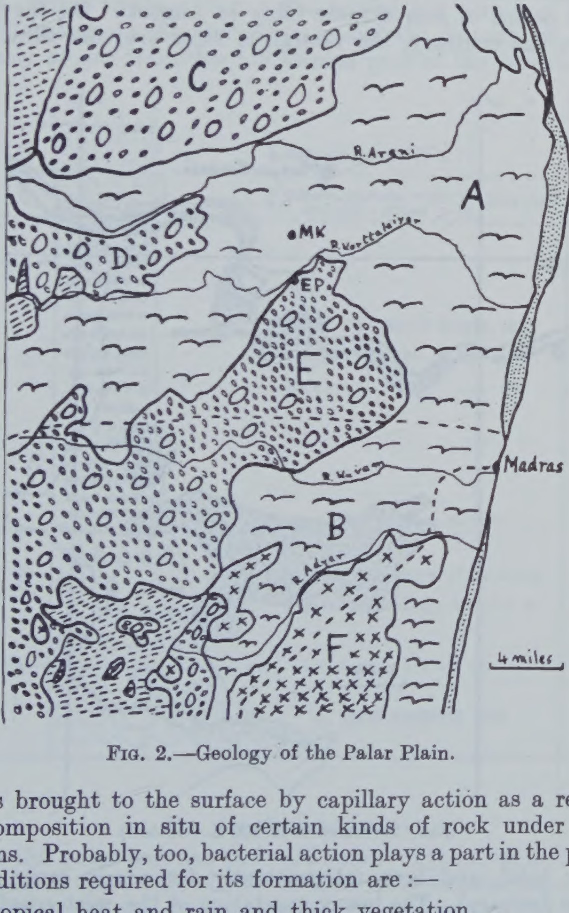

Fig. 2.—Geology of the Palar Plain.

(1) Tropical heat and rain and thick vegetation.

(2) Alternating wet and dry seasons, each of several months' duration.

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[1] See P. Lake in *Mem. Geol. Surv. I.*, xxiv, 1891, 217; J. M. Maclaren in Geol. Mag., 1906, 536 seq.; L. L. Fermor in Geol. Mag., 1911 and 1915, and *Mem. Geol. Surv. I.*, xxxvii, 1909, 370–89; C. S. Fox, *Mem. Geol. Surv. I.*, xlix, 1923.

(3) An elevated level or gently sloping surface, imperfectly drained.

(4) A subsoil that will retain moisture for long periods so that the interspaces of the weathered rocks are filled with water in the wet season, but are practically dry at the height of the dry season.

Such conditions exist to-day on the Malabar coast of India, where the annual rainfall averages about 120 inches, most of it falling within a period of four months (May to August). On the Madras coast, on the contrary, the rainfall is little over one-third of the Malabar total, and lasts intermittently for nearly seven months (June to January). The heavy vegetation of the west coast retains the moisture in the soil: the more precarious flora of the east coast does little to impede the run-off of the rainfall to the sea. In our opinion it is impossible for laterite to form under existing climatic conditions on the Madras coast. Yet laterite abundantly occurs in this area, sometimes still in situ, sometimes redeposited, having been denuded and washed down into its present position by torrent

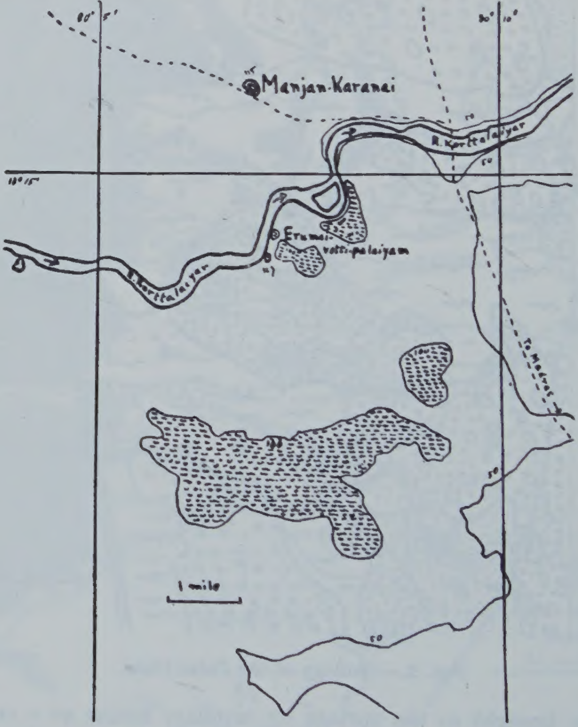
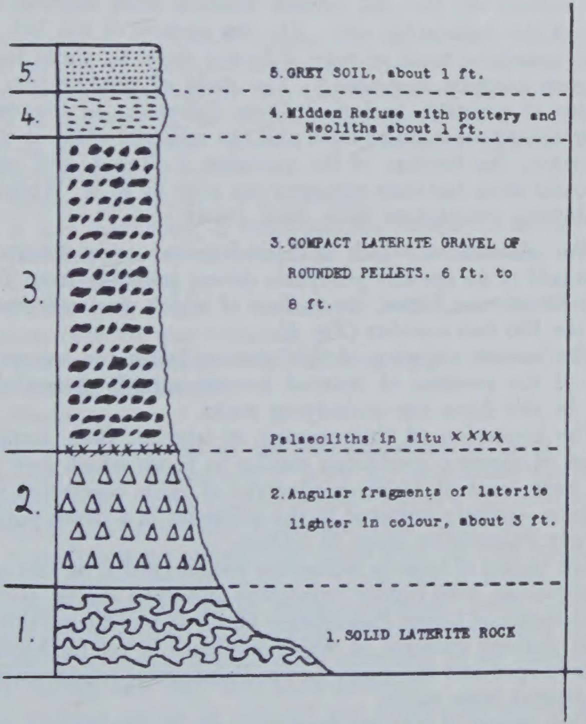


Fig. 3.—Area over 100 ft. (dotted).

action. In this redeposited laterite occur numerous Lower Palaeolithic implements, the tools themselves being often encrusted with laterite.

An interesting site, where the matter can be well studied, adjoins the village of Manjan-Karanai, which lies within 1½ miles of the north bank of the Korttalaiyar river, some 3 miles west of the Madras–Calcutta road bridge, which is about 16½ miles from Madras. Close to the village a flat-topped hill rises to a height of some 60 feet above the alluvial plain and 111 feet above sea-level. Obviously at one time this hill formed part of the laterite plateau which at this point bars the eastward course of the river and deflects it northwards past the village of Erumai-vetti-palaiyam (Figs. 2 and 3). Much of the laterite capping has been quarried away in recent times for road metal, and the quarry face has been carefully studied by Mr. Richards and Mr. Cammiade, as well as by Mr. Vinayak Rao, an officer of the Geological Survey of India.[1] The following strata are exposed (Fig. 4) :—



5.
5. GREY SOIL, about 1 ft.
4.
4. Midden Refuse with pottery and Neoliths about 1 ft.
3.
3. COMPACT LATERITE GRAVEL OF ROUNDED PELLETS. 6 ft. to 8 ft.
Palaeoliths in situ × × × ×
2.
2. Angular fragments of laterite lighter in colour, about 3 ft.
1.
1. SOLID LATERITE ROCK

FIG. 4.—Manjan-Karanai.

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[1] R. Bruce Foote also examined the site, but before quarrying operations had started.

The line of demarcation between the top of layer 2 and the bottom of layer 3 is very abrupt; there is no sign of any transitional formation. Actually it was along the line of junction of these two beds that most of the in situ Palaeolithic artifacts were found, and there was not one bit of quartzite here which did not bear marks of human handling. Layer 3 appears as a sort of rubble filling up pockets in the underlying laterite formation, and as this rubbly material (= detrital or pellet laterite) is of no use for road metal, it is left standing as pillars by the quarrymen (Plate X). We believe that this deposit represents the infilling of a gully or gullies in the surface of the old laterite plateau with lateritic debris, washed off the surface by rain. On the surface of the hill can be collected quartzite tools of very different date to those found in the deposit already described.[1] The state of preservation of the two series of quartzite tools is entirely different: in the one case the quartzite appears quite fresh and the colloidal silica is present, in the other, the texture of the quartzite is altered, and much of the colloidal silica has been removed (see note by S. W. Wooldridge). The following conclusions have been drawn:—

(1) The plateau of which Manjan-Karanai once formed part is a remnant of an ancient peneplain dating probably from Tertiary or early Pleistocene times, the surface of which was well over what is now the 100 feet contour (Fig. 3).

(2) The laterite capping of this plateau (with the exception, of course, of the pockets of detrital laterite already described) was formed in situ from the underlying rocks.

(3) The formation of this capping of laterite, then, implies the existence of climatic conditions similar to those which now prevail on the west coast of India, productive of rank vegetation and, in our opinion, entirely unsuited to the existence of a dense population in an early Palaeolithic stage of culture.

(4) The period of laterite formation was succeeded by one of much drier conditions, with lighter vegetation and open spaces, favourable to the existence of Lower Palaeolithic man. It was during this period that the earliest cultures of which evidence is yet forthcoming in India developed and the many Lower Palaeolithic implements found in the district were made.

(5) This period of cultural florescence was followed by an epoch of violent rains, in the course of which much of the plateau was completely destroyed. The erosion may perhaps have been accentuated by a rise in the general level of the land, with the consequent enhancement of the abrading and transporting power of rivers and streams. Some of the debris that was washed down found its way into the pockets in the laterite on what is now the top of the hill at Manjan-Karanai, and this formed the deposit we have called

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[1] Polished celts of diorite, some fragments of pottery, and an etched carnelian bead have also been found above the detrital laterite.

detrital or pellet laterite (layer 3.). Naturally implements must have also occurred in the debris, and so we find them to-day in this detrital laterite.

(6) The absence of colloidal silica observed in the case of so many of these early artifacts found in the detrital laterite would seem to indicate a recurrence of wet, laterite-forming conditions subsequent to the filling of the pockets.[1]

(7) The typology of the surface finds suggests that, after the filling of the pockets, the hill was tenanted by a people whose culture was different from that of their Lower Palaeolithic predecessors and very much more recent in time.

The sequence of climatic changes in South-East India suggested by the section at Manjan-Karanai is apparently corroborated when another section studied by Mr. Cammiade, on the left bank of a stream to the west of the village of Kannâpuram of the Pôlavaram Taluk in the Godavari district, is considered (Plate X). The observations were as follows :—

(6) Surface soil, mostly washed away.

(5) A thin sprinkling of small reddish pellets, seemingly laterite.

(4) Reddish brown alluvium, 12 feet in thickness. Bones of bison and deer occur.

(3) Pebble bed, 1 foot in thickness. It is from this bed that the fine ovate (Fig. 5) was obtained.

(2) Yellowish, alkaline sand interspersed with a little bluish clay, 3 feet in thickness.

(1) Gneiss.

Layer 2 is the result of the decomposition of layer 1, perhaps subsequent to the deposition of layer 3. This latter was laid down by torrent action during a damp period. Layer 4 indicates the setting in of quiet conditions and bison and deer abounded. In layer 4 occur some limestone nodules and these with the thin band (layer 5) of pellet laterite would seem to argue for a return of damper conditions. However, as at Manjan-Karanai, while there is thus evidence for a return of somewhat damper conditions there is as yet nothing to prove definitely the existence of an intervening dry period, though this may well have occurred.

It is perhaps unwise to attempt any exact correlations with East Africa until the results obtained by the expedition under Dr. Leakey, now in Kenya, are completed and published. There is no doubt, however, that Lower Palaeolithic man lived there under favourable conditions and that these were followed by the damp conditions of a pluvial period. After another dry period a further pluvial period set in, after which came still another dry epoch, since which time the climatic changes have been less extreme. But it is chiefly with the counterpart in South-East India of the earlier pluvial period of East Africa that we have been dealing. Perhaps further work in South-East India will demonstrate the Indian counterparts of the other climatic changes which have been shown to have occurred in East Africa.

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[1] As a result of this evidence it might be possible to suggest that a second dry period intervened between the damp period during which the detrital laterite was deposited and the damp period which caused the implements to begin to lose their colloidal silica. However it can, of course, always be argued that this lateritization of the implements took place at the end of the same damp period during which they and the detrital laterite were being washed down and deposited at Manjan-Karanai.

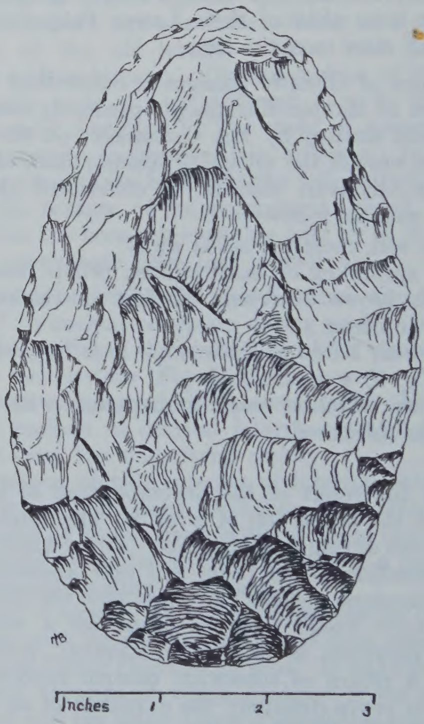
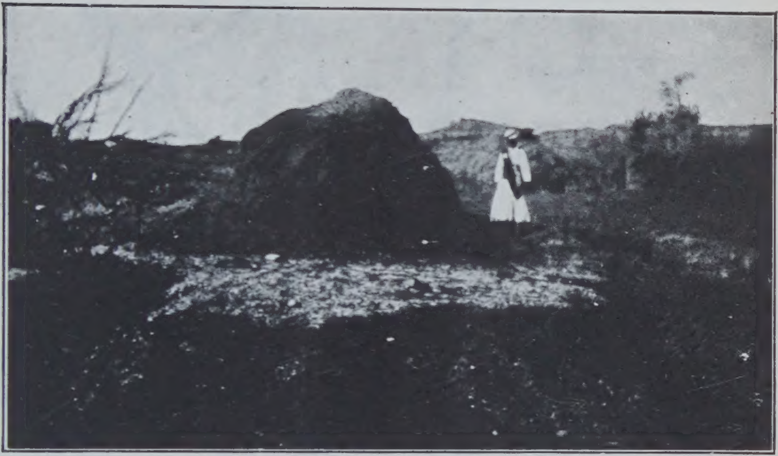


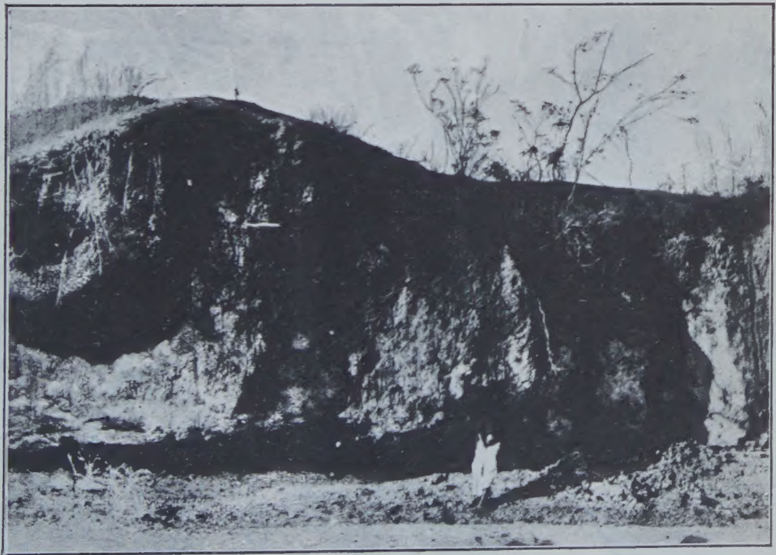
Fig. 5.—Ovate from Kannâpuram.

Palaeolithic Artifacts from Manjan-Karanai.

A number of quartzite implements from the detrital (= pellet) laterite have been examined. Judging from the state of preservation of the tools three groups can be distinguished. In the first of these there are one or two specimens, found at the base of the deposit, which are chocolate brown and heavily rolled. On typological grounds they would be classed as Acheulean if they had been found in Europe (Fig. 6, No. 4). Next there is a group numbering over twenty specimens also found at the base of the bed. They are



PILLAR OF DETRITAL LATERITE AT MANJAN-KARANAI.



SECTION AT KANNÁPURAM NEAR WHERE THE OVATE WAS FOUND.

[To face p. 200.

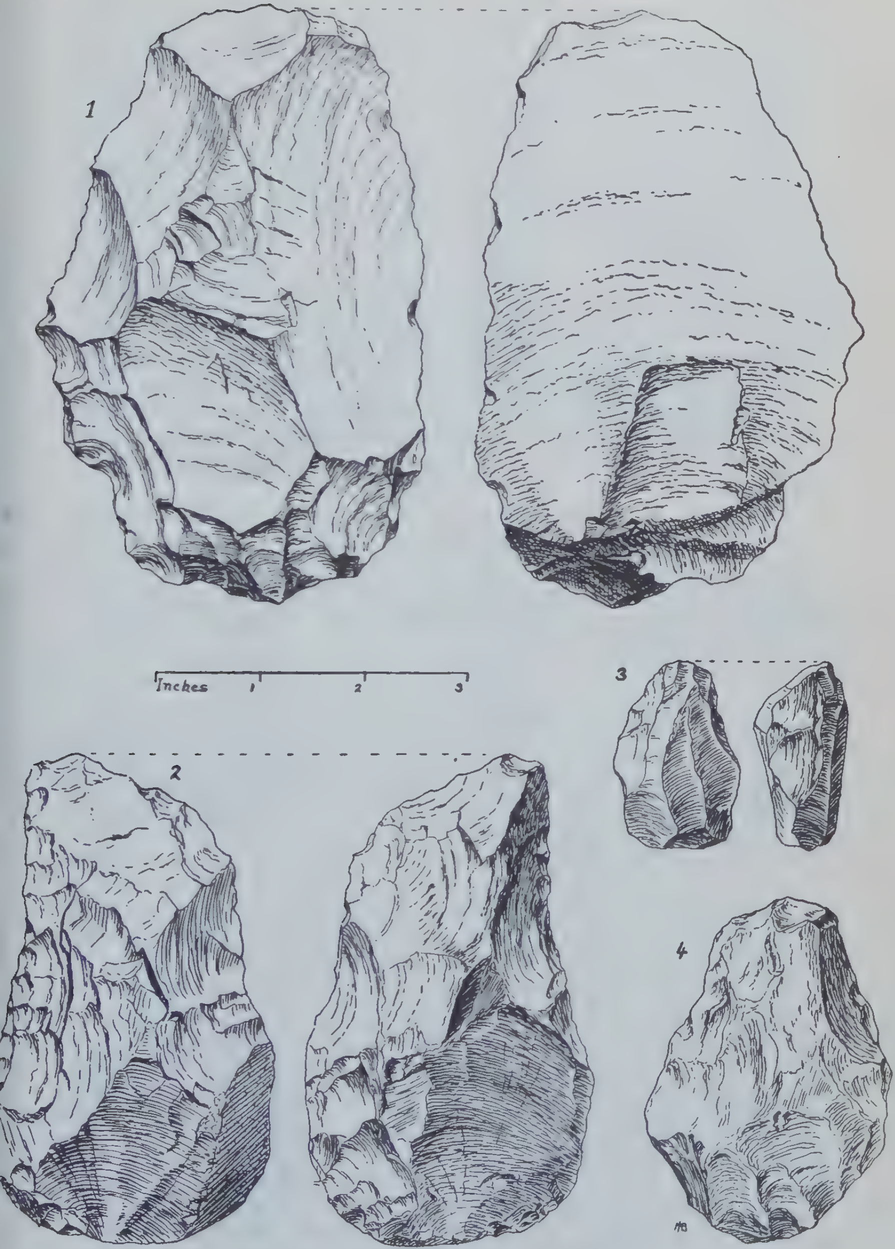


FIG. 6.—Quartzite tools from Manjan-Karanai.

stained a deep orange, like the laterite which surrounds them, and to some extent there has been a removal of colloidal silica in a number of cases. This is probably due to the process of lateritization operating after the implements were deposited. The last group is similar to the one just described, except that the tools have been much less stained. Most likely examples of this group occurred higher up in the laterite bed; actually the specimens collected were picked up from the surface of the ground, having probably been washed out of the deposit. The implements in the last two groups include *coups de poing* (Fig. 7, No. 1), among which is a late type (Fig. 7, No. 8), cleavers (Fig. 6, Nos. 1 and 2), choppers (Fig. 7, Nos. 2, 3, and 6), discs (Fig. 7, No. 7), flakes (Fig. 7, Nos. 4 and 5), and a scraper of a somewhat special type (Fig. 6, No. 3). I believe all these tools belong to the end of Series I and the beginning of Series II (see *Antiquity*, September, 1930). In age, therefore, they must be placed at the very end of the Lower Palaeolithic and the commencement of the Middle Stone Ages. The implements can be matched in every way from late Stellenbosch industries in South Africa.

The ovate from the second site is an exceedingly fine example, especially when it is realised that the material from which it is made is quartzite. Unlike the specimens from Manjan-Karanai, it is grey in colour, and very fresh in appearance, being hardly at all rolled or altered by subsequent weathering. Typologically, it is typically Acheulean in age.

Note on the Petrography of the Quartzite Implements.

I have examined the quartzite artifacts from a petrographical point of view, and have arrived at conclusions entirely compatible with those enunciated by Mr. Philip Lake. It seems quite clear that the rotting of the quartzite is due to the removal of silica in solution, in a colloidal condition. Microscopic examination of the powder obtained by crushing the soft rotted material shows it to consist of curious spicular pieces of silica. These are not of organic origin, but are purely residual, the insoluble, or at least the undissolved, portion of sand grains that have suffered peripheral corrosion. In view of the fact that the process of lateritization, whatever its details, involves the removal of silica in large quantities, we may, I think, certainly regard the condition of the quartzite as a result of the process. It appears to be strictly comparable with the rotting of flint pebbles in certain Eocene deposits, such as the Blackheath Beds at Knockmill, Kent. In these cases unweathered black flint is reduced to a white substance which easily crushes to powder in the fingers. It is true that in this case we are supposedly dealing with a mixture of crystalline and amorphous silica, while the quartzite is wholly crystalline, but I have thought for some time that the known tropical conditions of Eocene times were probably a necessary

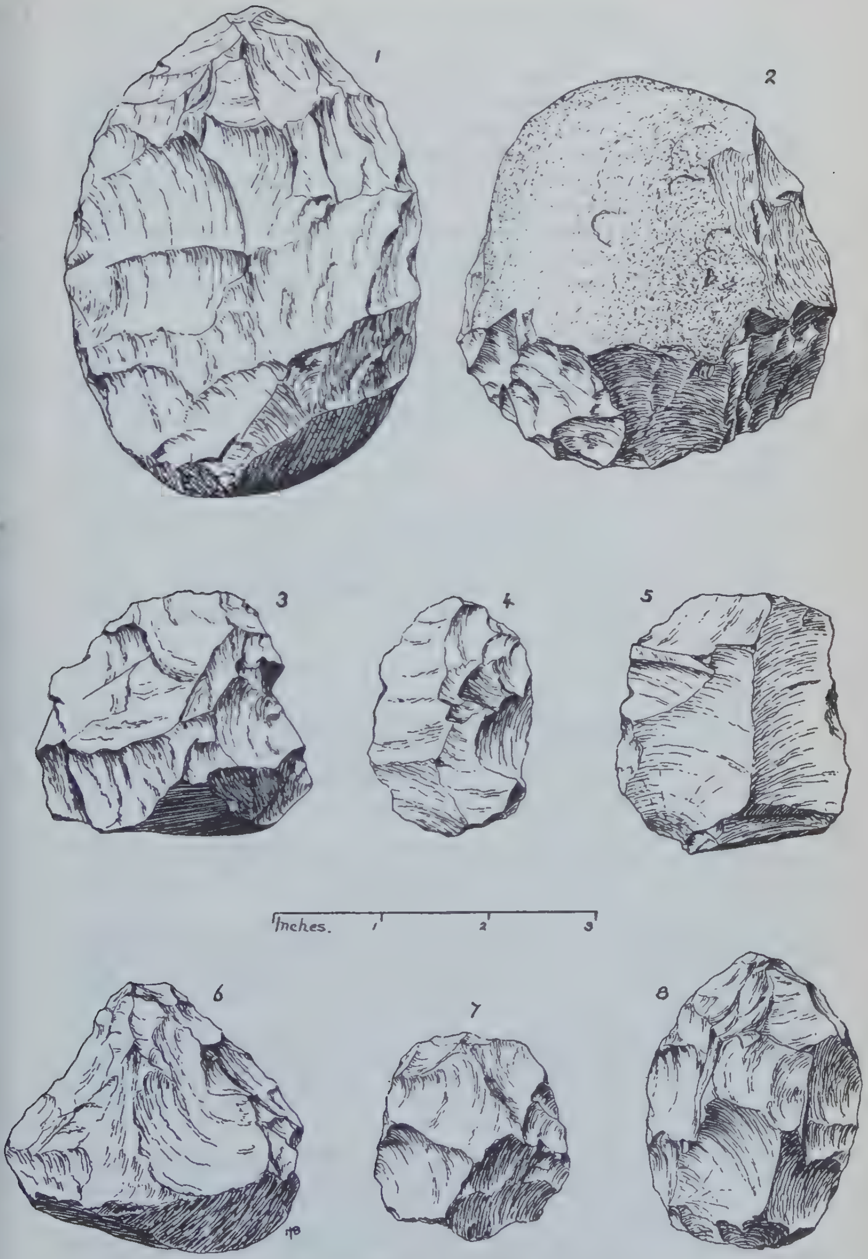


FIG. 7.—Quartzite tools from Manjan-Karanai.

condition for this type of alteration. An even closer analogy is presented by the Tertiary sarsens which sometimes are in the condition of true quartzite, but elsewhere are soft and crumbling. This has generally been tacitly assumed to be due to imperfect silicification; it is at least as likely to be due to a phase of the lateritization process, involving desilication.

It may be noted in conclusion that the process of dissolution of silica would in any case tend to be cumulative in view of the fact that solubility in general increases with decrease in grain size and the resulting increase in aggregate surface. Thus as soon as the quartzite grains ceased to be in contact the process would gather way.

In the light of the examples mentioned, I should certainly regard this type of "desilication rotting" as evidence of heat and humidity, combined with conditions of free drainage which would prevent the accumulation in situ of potentially recementing solutions.

S. W. Wooldridge.

Note on the Geological Evidence adduced from the Section at Manjan-Karanai.

I agree that the geological evidence strongly supports the general conclusions of the authors, but there are one or two points to which I should like to draw attention.

(1) When the original laterite was formed the climate must have been wet, much wetter than it is at present.

(2) The bed of angular fragments suggests a drier period, during which the surface of the original laterite was broken up.

It should be noted, however, that this bed did not accumulate till *after* the pocket in which it lies was formed, and it does not itself include any of the palaeoliths which were found.

If the pocket had been eroded after the surface of the laterite had been broken up and the palaeoliths scattered over it, and if the loose material had then been swept into the pocket, the palaeoliths would have been found *in* the bed of angular fragments.

The fact that there is an abrupt break at the top of this bed and that the implements are found there seems to prove that both the pocket and the bed itself were in existence while man was occupying the surrounding country. It was during the wet period indicated by the succeeding bed that the implements were washed into the pocket.

I do not think that the erosion of the pocket requires any separate wet period. It may have taken place during the original laterite period, which must have been a very long one, or during the earlier part of the succeeding dry period. I should be inclined to compare it with the fissures in the plateau laterite of Malabar rather than with a nala.

(3) The bed of pellety laterite lying upon that of angular fragments, without any transition from one to the other, points to the recurrence of a rainy climate.

(4) The absence of colloidal silica in the palaeoliths proves that there was a wet period after they were made, and the position

of these palaeoliths indicates that this was the period during which the bed of pellety laterite was washed into the pocket.

(5) The fact that there is no later formation of laterite and the condition of the later set of artifacts show that the wet period had ceased before these artifacts were manufactured.

Of these five inferences, 1, 4, and 5 may be considered as certain. Definitely to prove 2 and 3 would require one or two more cases showing a similar succession.

The pocket in the quarry face represents local episodes, which may perhaps have been due to local causes. Another section showing a bed of angular fragments followed abruptly by a bed of pellety laterite would strengthen the argument greatly, even if no implements were found at the junction. If such implements, with the colloidal silica removed, *were* found at the corresponding position in this second case also it would be practically conclusive.

Except as regards the erosion of the pocket it will be seen that my inferences are in conformity with the conclusions of the authors; and even without further confirmation there is strong evidence of:

4. Dry period, up to the present, including the period of the later artifacts.
3. Wet period, earlier artifacts washed into pocket.
2. Dry period, earlier artifacts manufactured.
1. Wet period, during which the original laterite was formed.

PHILIP LAKE.

Notes on Two Species of the Genus *Ampyx*.

By F. R. COWPER REED, Sc.D., F.G.S.

(PLATE XI.)

AMPYX (LONCHODOMAS) PENNATUS (Salter MS.) La Touche.

(Pl. XI, Figs. 5–7.)

HEAD-shield acutely triangular. Glabella elongated, subpentagonal, widest across middle, gently convex or subcarinate, without furrows or lobes, having anterior half freely projecting in front of cheeks and produced into a long slender straight horizontal spine grooved along its upper and lower surfaces, fully twice the length of the glabella. Axial furrows nearly straight, diverging anteriorly, with a small deep slit-like pit at their anterior end. Fixed cheeks smooth, broadly triangular, nearly equilateral, reaching half-way up the glabella, with posterior lateral angles slightly curved back. (Free cheeks unknown). Facial sutures slightly sigmoidal. Pleuro-occipital furrow straight, strong, marking off rather broad band-like occipital segment; meso-occipital furrow and segment scarcely defined, smooth, without median tubercle.

Pygidium broadly triangular, short, with smooth conical axis reaching steeply bevelled broad striated border; pleural lobes smooth, except for short first curved interpleural furrow developed near lateral margin.

Dimensions.—Length of head-shield to base of frontal spine, 8–10 mm. Width of head-shield at base, 12–14 mm.

Remarks.—The head-shield which La Touche [1] figured as *Ampyx pennatus* Salter, MS., is now in the British Museum, and this and another in the same collection have been examined by the author. La Touche's figure of the head-shield is poor, and he gave no description of its characters. But as it is the first and only figure of the species so far published, it must be regarded as the type. This is unfortunate, as we have much reason to believe that Salter meant the name to be applied to a completely different type of head-shield, and the type specimen of this is in the Jermyn Street Museum, and is here described and figured under a necessarily new specific designation *edgelli* (see below).

There are several good specimens (Nos. 35661–4) of *A. pennatus* (Salt. MS.) La Touche, from the "Caradoc" of the Onny River, in the Jermyn Street Museum, one of which is a young individual (No. 35664) having the head, thorax, and pygidium complete, and measuring only 7 mm. in all in length; it has only five thoracic segments (the first of which is partly hidden, having been pushed under the head-shield). Raymond [2] considers this number of segments to be characteristic of *Lonchodomas* as distinct from *Ampyx* sens. str., which has six. Other specimens of the species are preserved in the Ludlow Museum (C.C. 70 in part). As regards the affinities of *A. pennatus*, it is clearly related to *A. portlocki* Barr.[3] (particularly resembling the examples from the Trinucleus shales of Scania figured by Olin [4]), and to *A. tetragonus* Ang. [5] (which is possibly identical with *A. portlocki*), and to *A. macallumi* Nich. and Eth.,[6] from Girvan. But the American species, *Lonchodomas politus* Raymond,[7] seems still more closely allied, and *L. sublaevis* Raym.[8] and *L. longirostris* Cooper [9] are also much like it. In the last mentioned species there are said to be "narrow elongate pits" at the anterior ends of the axial furrows on the head-shield, and the segmentation of the pygidium is practically obsolete, both of which features are found in our species. A form allied to *A. macallumi* with the glabella carinated has been described from the Ordovician of Burma,[1] but it more resembles the examples of *A. rostratus* Sars figured by Schmidt [2] from Stages C 1 and C 2 of the Baltic Ordovician, and the first figure of *L. politus* Raym. (op. cit.). All these belong to the subgenus or genus *Lonchodomas* as defined by Raymond, and we must refer to it also the trilobite from Girvan, described by the author [3] as *Ampyx depressus* Ang., which is possibly referable to *A. portlocki* Barr.

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[1] La Touche, *Handbook to the Geology of Shropshire*, 1884, 57, pl. iii, fig. 56.

[2] Raymond, *Bull. Mus. Comp. Zool. Harvard*, lxvii, No. 1, 1925, 30.

[3] Barrande, *Syst. Silur. Bohême*, i, 1852, 636, pl. xxx, figs. 24–8.

[4] Olin, "Chasmops o. Trinucleusskif. Skåne," *Medd. Lunds. Geol. Fältklubb*, ser. B, No. 1, 1906, 69, t. iv, figs. 5–8.

[5] Angelin, *Palaeont. Scand.*, 20, t. xvii, fig. 2.

[6] Nicholson and Etheridge, *Mon. Silur. Foss. Girvan*, fasc. 2, 1879, 180, pl. xii, figs. 9–12; Reed, *Lower Palaeoz. Trilob. Girvan* (Palaeont. Soc.), pt. i, 1903, 21, pl. iii, figs. 11, 12.

[7] Raymond, op. cit., 39, pl. ii, figs. 8–10.

[8] Ibid., 40, pl. ii, figs. 11, 12.

[9] Cooper, *Amer. Journ. Sc.*, xx, 1930, 370, pl. iv, figs. 11–18.

AMPYX (RAPHIOPHORUS) EDGELLI sp. nov.

(Pl. XI, Figs. 1, 1*a*, 2, 3, 4.)

Head-shield semicircular; glabella rounded, swollen anteriorly, subovate, short, widening, and somewhat projecting in front and overhanging edge of head-shield, with a stout median rounded spine-base or tubercle near its anterior end, from which a narrow rounded, raised, median band or carina runs back to the slightly elevated annular base; a narrow elongated sublanceolate longitudinal lateral lobe extends along each side for about two-thirds the length of glabella parallel to the axal furrows, with a shorter, broader, subrhomboidal well-defined lobe on its inner side, and a small faint subcircular area between it and the median band at about its middle. First (anterior) lateral furrow arising at end of axial furrows sloping very obliquely back to deep pit, then bending more inwards to define front end of subrhomboidal lobe, and connected by a short longitudinal furrow with a transversely oblique triangular pit at base of subrhomboidal lobe, which has on its outer side a short notch (? representing second lateral furrow). Meso-occipital furrow strong, broad, with traces of small occipital lobe on each side; meso-occipital segment with stout median tubercle or spine-base; pleuro-occipital furrow strong, straight. Fixed cheeks triangular, smooth, flattened, wider than base of glabella; free cheeks narrow, band-like, bent down, with very narrow, flattened margin and having genal angles produced into long, backwardly directed spines, deeply grooved below for their whole length, arching at first outwards before running back nearly parallel to axis of body for about twice the length of the head-shield.

Pygidium triangular; axis conical, indistinctly trilobed, rapidly tapering to reach narrow marginal furrow, annulated in middle with numerous narrow rings. of which the first seven or eight are distinct, slightly undulate, and have small lateral swellings. Pleural lobes flat, carrying 5–6 pairs of flattened, well-defined, simple pleurae, curving slightly forwards laterally and ending against marginal furrow which separates off broad steeply bevelled border with raised inner edge.

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[1] Reed, *Palaeont. Ind.*, n.s., vi, Mem. 1, 1915, 25, pl. v, figs. 4–6.

[2] Schmidt, "Rev. ostbalt. Trilob., Abt. IV" (*Mem. Acad. Imp. Sc. St. Petersb.*, ser. vii, xlii, No. 5, 1894), 85, t. vi, figs. 29–33.

[3] Reed, *Lower Palaeoz. Trilob. Girvan*, pt. i, 1903, 17, pl. iii, figs. 6–7.

Remarks.—This species is founded on a specimen of a cranidium from Horderley Quarry (No. 35648), in the Museum of Practical Geology, which was presented by Salter, and, as far as can be traced, was the actual specimen to which he attached the MS. name *pennatus.* This name was first published by him in 1865, in his *Catalogue of the Palaeozoic Fossils in the Museum of Practical Geology, Jermyn Street*, p. 4, and the specimen (No. 35648) was subsequently re-catalogued with this name in 1878 in the *Catalogue of Cambrian and Silurian Fossils in the Museum of Practical Geology*, p. 42, and is recorded there as presented by Salter, but the registered number was attached to it later. These particulars have been kindly furnished me by Dr. Kitchin. But no description of this specimen was ever published, nor was any figure of it given. As mentioned above, La Touche, in 1884, figured a completely distinct species under Salter's name in his *Handbook to the Geology of Shropshire*, pl. iii, fig. 56, though he gave no description of its characters. A new specific designation must, therefore, unfortunately be found for the species to which Salter seems to have originally given the name *pennatus.* The type is his specimen, No. 35648 in the Jermyn Street Museum, and we may propose for it the name *edgelli.*

This specimen has not the free cheeks or genal spines attached, but another specimen here figured (No. 35644), from the Onny River, has these parts preserved, though the glabella is very imperfect. A third example (No. 35645), consisting of a fairly good cranidium, also exists in the Wyatt Edgell collection, in the Jermyn Street Museum, and another (C.C. 70, right-hand lower specimen on tablet) from Horderley is preserved in the Ludlow Museum.

As regards the affinities of this species, we may draw attention to the many points of resemblance to *A. foveolatus* Angelin,[1] and to a less extent to *A. mammillatus* Sars [2] and *A. costatus* Ang.[3] The pygidia of these species possess characters closely similar to those of the isolated pygidia Nos. 35641, 35642, 35646, in the Jermyn Street Museum, which come from the same horizon and locality as the head-shield on which our new species is founded, so that we may probably refer them to it, and two of them are therefore figured here. The lobation of the glabella is somewhat hard to interpret in the terms of the typical furrows, but the lateral pits and furrows in *Ampyx* and its subgenera seem to be in various stages of obsolescence, and there is considerable variation in their development in the

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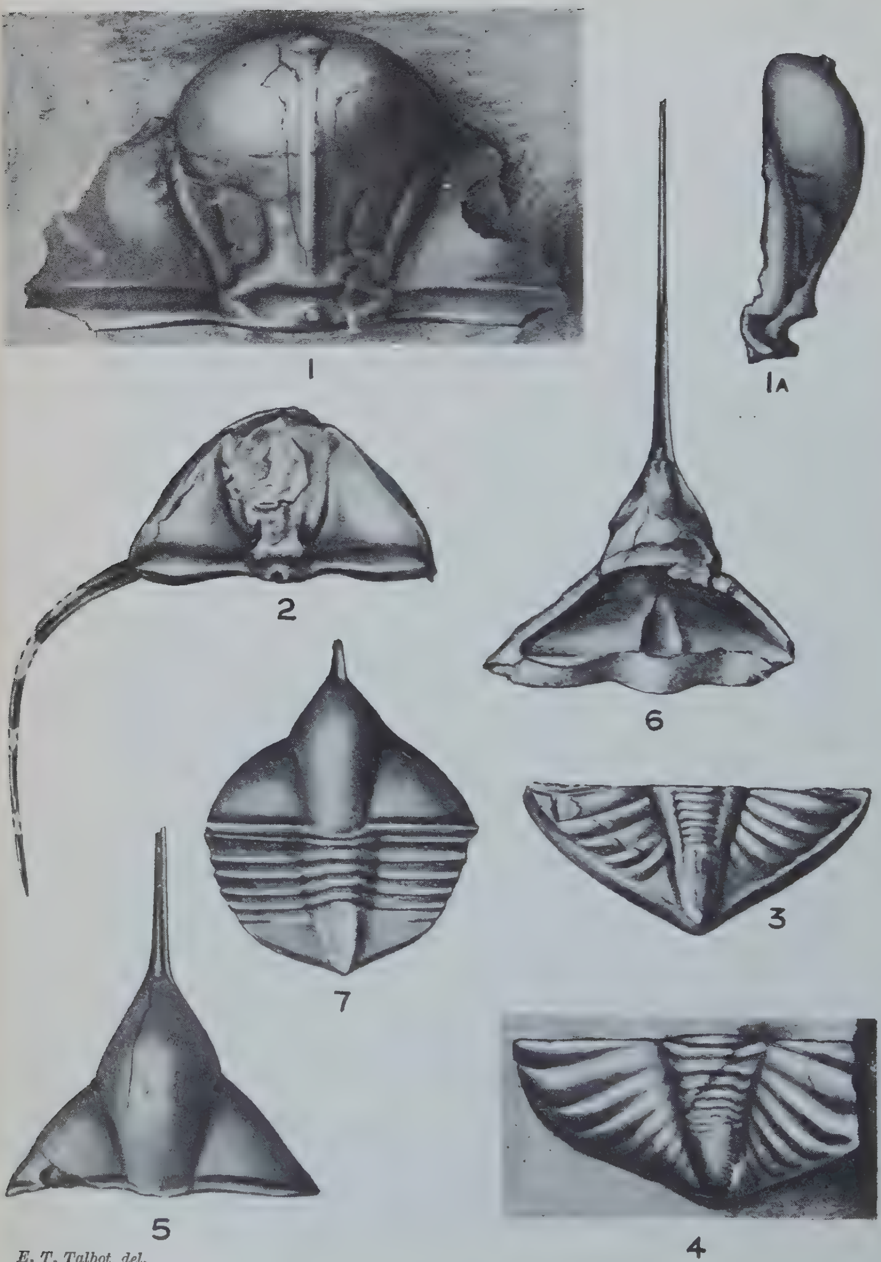
[1] Angelin, *Palaeont. Scand.*, 1854, 80, t. xl, figs. 2, 2*a*; Warburg, *Bull. Geol. Instit. Upsala*, 1925, 225, pl. vi, fig. 10.

[2] Angelin, op. cit., 80, t. xl, figs. 3, 3*a*–*c*.

[3] Ibid., 80, t. xl, figs. 1, 1*a*; Schmidt, op. cit., 1894, 84, t. vi, figs. 24–6; Hadding, *Kongl. Fysiogr. Sällsk. Handl.*, n.f., Bd. 24, No. 15, 1913, 74, t. vii, fig. 17.



E. T. Talbot, del.

Two Species of Ampyx.

To face p. 209.]

different members of the subgenus *Raphiophorus*, to which all those species above mentioned belong.[1]

Dimensions :—

	mm.
Length of head-shield to front of glabella (No. 35648)	10·00
Width of ditto at base	c. 21·00
,, of glabella in front	8·75
,, of ditto at base	5·00
Length of pygidium (No. 35646)	17·00
Width of ditto	8·00

EXPLANATION OF PLATE XI.

FIG.

1.—*Ampyx* (*Raphiophorus*) *edgelli* sp. nov. Imperfect middle-shield (No. 35648 Mus. Pract. Geol.). × 4. Horderley Quarry.

1*a*.—Ditto. Profile view of same specimen. × 4.

2.—Ditto. Imperfect head-shield with genal spine. (No. 35644, Mus. Pract. Geol.) × 2. Onny River.

3.—Ditto. Pygidium (No. 35646, Mus. Pract. Geol.). × 2½. Horderley Quarry.

4.—Ditto. Ditto (No. 35641, Mus. Pract. Geol.). × 2½. Same locality.

5.—*Ampyx* (*Lonchodomas*) *pennatus*, Salt. M. S. Head-shield (No. 35662 Mus. Pract. Geol.). × 3½. Onny River.

6.—Ditto. Complete enrolled specimen showing lower surface of glabellar projection, rostral spine and pygidium (No. 35661 Mus. Pract. Geol.). × 3½. Same locality.

7.—Ditto. Complete young individual (No. 35664, Mus. Pract. Geol.). × 6. Same locality.

The Metamorphosed Limestones and Associated Contaminated Igneous Rocks of the Carlingford District, Co. Louth.

BY G. D. OSBORNE, Dept. of Mineralogy and Petrology, Cambridge.

(PLATES XII AND XIII).

FULL SCHEME.

INTRODUCTION AND ADVANCE SUMMARY.

PREVIOUS RECORDS AND FIELD OCCURRENCE.

PETROGRAPHY.

1. Rocks showing fairly low-grade thermal metamorphism.
2. Rocks showing medium to high-grade thermal metamorphism.
    - (*a*) Forsterite-brucite-spinel marbles.
    - (*b*) Marbles almost devoid of silicates.
    - (*c*) Calc-silicate and calc-magnesian-silicate rocks.
        - Petrographical details.
        - Textural features.
3. Rocks which have been affected by pneumatolytic action.
    - (*a*) Rocks whose essential constituents are phlogopite, diopside, vesuvianite, pleonaste, and calcite.
    - (*b*) Altered vesuvianite rock.
    - (*c*) Assemblages with custerite and monticellite.

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[1] Raymond, *Bull. Mus. Comp. Zool. Harvard*, lxvii, No. 1, 1925, 30.

GENERAL DISCUSSION INCLUDING GENESIS OF THE METAMORPHIC ROCKS.
- 1. Rocks showing no connection with pneumatolytic action.
  - (a) Forsterite-brucite-spinel marbles.
  - (b) Calc-silicate and calc-magnesian-silicate rocks.
    - (i) General aspects: grades of metamorphism and diaphthoresis. zonal structures.
    - (ii) General genetic considerations.
  - (c) Silica-poor assemblages.
- 2. Rocks showing pneumatolytic effects: custerite-monticellite types.
- 3. Skarn-like modifications of the hornfelses.

CONTAMINATED IGNEOUS ROCKS.
- Pegmatites with wollastonite, hedenbergite, and andradite.

ACKNOWLEDGMENTS.

EXPLANATION OF PLATES.

INTRODUCTION AND ADVANCE SUMMARY.

THE Carlingford-Barnave district falls within the boundaries of Sheet 71 of the Ordnance Survey of Ireland, and forms part of a broad promontory lying between Carlingford Lough on the north-east and Dundalk Bay on the south-west. The greater part of this promontory is made up of an igneous complex of Tertiary age which has invaded the Silurian slates and quartzites and the Carboniferous Limestone Series. This complex has not yet been investigated in detail, but for the purposes of the present paper certain references to it are necessary, and these are made below. The prevalence of hybrid-relations and contamination-effects between the basic and acid igneous rocks of the region is a very marked feature, and because of this it has been difficult at times to decide which types have been responsible for the various stages of the metamorphism.

As an advance summary, the following comprehensive statement may be made. The Carboniferous limestone, variable in its impurity-content and in the degree and localization of dolomitization, was invaded by some members of the earlier basic group of the Tertiary intrusives. This action produced strong contact metamorphism without the addition of magmatic material, the chief products being calc-magnesian-silicate rocks and forsterite-spinel-periclase marbles. After an interval of time, acid magma was injected into the basic rocks giving hybrids of every gradation between aplite-granophyre and gabbro-eucrite groups. Pneumatolytic action, genetically connected with the acid phase, affected the marbles and calc-magnesian-silicate rocks producing some very interesting and rare assemblages. Skarn-like modifications of the metamorphic limestones were developed in the vicinity of the acid injections, but the position of this occurrence in the sequence of events is difficult to determine. Towards the end of the period of invasion of the acid magma, pegmatitic satellites of this magma assimilated a certain amount of lime (probably chiefly from calcite) and reacted with the skarns to produce some remarkable contaminated igneous rocks, which contain abundant crystals of hedenbergite, andradite, and wollastonite, the last-named having all the appearances of an early crystallizing pyrogenetic mineral. The last event in the igneous cycle was the injection of a series of basaltic dykes and sheets which have produced practically no change in the limestones traversed by them.

PREVIOUS RECORDS AND FIELD OCCURRENCE.

The Carlingford region, together with the Newry and Mourne districts to the north and north-east, has long been known to geologists and several contributions to the literature have been made during the last hundred years. The chief studies however, have been upon the igneous rocks, and only the briefest mention of the metamorphism of the Carboniferous limestone has been made in certain papers and in various textbooks. The only connected account of the Carboniferous rocks was given in 1878 in a Geological Survey Memoir by W. A. Traill,[1] while in 1856 S. Haughton[2] published some analyses of certain rocks from the district, and referred very briefly to the metamorphism. On the 1-inch geological map of Sheet 71 the numerous isolated outcrops of altered limestone are shown, and in the accompanying memoir it is explained that, in addition to these scattered occurrences, great masses of blue limestone occur in the environs of Carlingford and also form much of the lower ground to the south and south-east of this village.

It is convenient at this point to enumerate the exposures where the altered limestones have been studied in connection with the present work (see Text-fig. 1). These are (1) Main Carlingford Quarries; (2) Eastern face of Barnavave Mountain, especially Barnavave Quarry; (3) Col between Slieve Foye and Barnavave; (4) Grange Irish neighbourhood; (5) The Commons Quarry, 1½ miles south of Carlingford; (6) ¾ mile south-west of Slievenaglogh; (7) ¼ mile north of Jenkinstown Cross. Of these localities the best-known in connection with the lime-silicate rocks is Barnavave Quarry (2). Here, many years ago, the quarry exposed masses of limestone invaded by eucrite which often isolated great blocks of the sedimentary rock. Beautiful specimens of calc-magnesian-silicate rocks were then obtainable and splendid material was collected, some of which is now in the Petrological Collections of the Sedgwick Museum, and some in the Geology Department of the National University of Ireland. The examination of the rocks in both of these collections led the writer to make several visits to Carlingford, and an investigation of all the exposures showed that in addition to typical calc-silicate rocks there occurred in close proximity some contact-assemblages of exceptional interest, as well as certain contaminated granite-pegmatites.

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[1] *Mem. Geol. Surv. Ireland*, Sheet 71, and part of Sheet 60.

[2] *Quart. Jour. Geol. Soc.*, xii, 1856, 192.

The field-relations between the igneous and metamorphic rocks are in most cases very poorly displayed, and even in the Barnavave quarry it is difficult to make out the relations between the lime-silicate rocks, the skarns, and the contaminated pegmatites. The enlarging of the quarry in recent years has almost eliminated the limestones, and now only occasional blocks up to 5 feet in diameter are seen isolated in the eucrite. These blocks are frequently rounded, but there does not seem to be evidence that the adjacent basic rock has been changed in composition. However, it is extremely difficult to obtain suitable material to decide this point fully. On the quarry floor several masses from included blocks lie scattered, and these have supplied the material upon which a good deal of the present work has been based. Speaking generally, however, the progress of these studies has been handicapped by the very unsatisfactory nature of the field-relations.

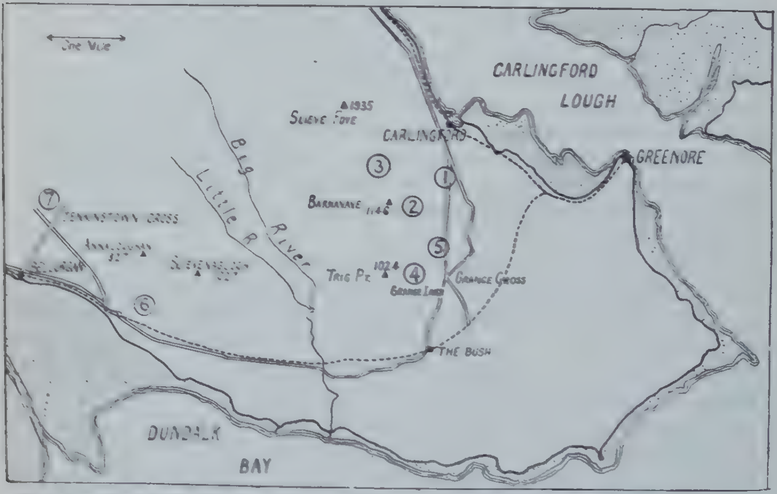

Fig. 1.—Map of Carlingford District, showing localities of altered limestones.

Petrography.

As a result of the thermal metamorphism and the succeeding pneumatolytic and metasomatic action the following minerals have been developed in the limestones :—

Grossular (*clinozoisite, vesuvianite*)
Andradite
Diopside (*tremolite, actinolite*)
Hedenbergite
Wollastonite
Forsterite
Spinel
(*Brucite*) from periclase
Edenite

Phlogopite
Monticellite
Custerite
Albite
Orthoclase
Microcline (*sericite*)
Andesine
Apatite
Scapolite

Vesuvianite
Clinozoisite-epidote
Hornblende
Sphene
Calcite
Quartz
Magnetite
Pyrite
Perovskite
Graphite (?)

The minerals written in italics have, with perhaps the exception of brucite, developed during changes which, it is believed, were not related to atmospheric weathering.

The metamorphic limestones may now be treated in groups as follows :—

1. *Impure limestones showing fairly low-grade thermal metamorphism:* Localities (2) and (7).

There is no need to consider the almost pure limestones which occur some distance from the contacts of the larger intrusives, or which have been intersected by dykes and sheets. Such rocks, at the most, have partially recrystallized without the formation of silicates.

Some of the impure limestones are little more than calcareous shales, and in many cases the changes wrought have caused recrystallization of calcite and silica without reaction. Patches of fine kaolinic and chloritic material and finely divided silica have suffered little change. In the calcareous streaks and lenses through those rocks which have been raised to a higher temperature grossular has developed, as, for example, about 80 yards from the eucrite at Barnavave. This mineral has generally passed over into vesuvianite due to changes following the thermal metamorphism. In other rocks, however, good crystals of clinozoisite are found with hornblende and calcite. The clinozoisite in this case is a true thermal product. The crystals show the forms (001), (100), (110), (011), and $(\bar{1}01)$, and while the sign is mostly positive, some epidote is indicated by occasional negative sign. The calcite is idioblastic in stumpy prisms with little cleavage. In some of these rocks tiny wisps of calcic scapolite showing (110) cleavage are found, while units of orthoclase and clear albite are sparingly present.

2. *Rocks showing medium to high-grade thermal metamorphism.*

(*a*) *Forsterite-spinel-brucite-marbles:* Locality (4).

These rocks are fine-grained and light-coloured with numerous black specks of magnetite, perovskite, and carbonaceous material. In thin section it is seen that calcite forms 70% of the rock. The forsterite is present in rounded grains with indistinct (010) cleavage. The sign is positive and the D.R. about ·036. Alteration to almost colourless serpentine is general, and complete pseudomorphs are common. Further alteration of the serpentine has not occurred.

Spinel is patchy in its distribution, often occurring in tiny rounded colourless grains; at other times, especially when pale-violet in colour, it is idioblastic with the cube-octahedron combination. Spinel was left as gritty particles after the rock had been digested with HCl. Brucite derived from periclase, in units up to 0·25 mm. in diameter, is quite common in these rocks. It is fibrous with negative elongation, and the acicular crystals lie scattered in all directions within the boundaries of the units. The cube-octahedron outlines of the pre-existing periclase are beautifully shown, although the original form has been somewhat distorted on account of the volume-change following the hydration of the parent mineral. As in the cases of the brucite in the Tirol predazzites and in the Skye marbles, the D.R. is never higher than about ·010, and clouding by carbonaceous inclusions is a common feature. There does not seem to be any hydromagnesite, which is distinguished by its somewhat lower refraction.

Perovskite is a rare accessory, and has features similar to that in the phlogopite rocks (see below). Amongst the patches of carbonaceous material some specks suggest the presence of graphite. By gradual disappearance of certain constituents the rocks become ophicalcites and predazzites in very local fashion.

(*b*) *Marbles almost devoid of silicates.*

Some of the more strongly metamorphosed limestones are coarse in grain, and in these diopside may occur sparingly, but wollastonite is the more common with fibrous-radial form, the tiny pseudo-prismatic crystals being developed in fringes and streaks in the marbles or at the junction of a pure marble and a layer which originally was a calcareous silt. The narrowness of the fringe indicates the limited extent to which diffusion and interaction have proceeded. In No. I.131 part of the rock is a marble carrying subordinate prisms of wollastonite, diopside, and dodecahedra of grossular. On the whole, carbonate-rocks carrying subordinate silicates are rare at Barnavave, and either the rocks show little excess calcite, or else CO_2 has been entirely eliminated. The consideration of these now follows :—

(*c*) *Calc-silicate and calc-magnesian-silicate rocks.*

The following are all quartzless assemblages with occasional residual calcite. Staining tests have shown that dolomite does not occur in any of the rocks. In the following list the italicized minerals are those developed by retrogressive metamorphism.

1. Grossular (*vesuvianite* or *clinozoisite*)-diopside.
2. Grossular (*vesuvianite* or *clinozoisite*)-wollastonite-diopside.
3. Grossular-diopside-vesuvianite-wollastonite.
4. Diopside-wollastonite.
5. Grossular (*vesuvianite* or *clinozoisite*)-wollastonite.
6. Grossular (*vesuvianite*)-wollastonite-vesuvianite.
7. Wollastonite-andesine-diopside.
8. Wollastonite-calcite.
9. Diopside-microcline.

In addition to the listed mineral-phases, which are the most significant from the standpoints of genesis and classification, it is to be noted that many accessory minerals occur, and occasionally one or other of these may become important. These minerals are orthoclase, albite, apatite, magnetite (haematite, limonite), sphene, and prehnite. The status of the last-named is in doubt, but the rest are genuine thermal products. In some of the rocks related to skarns, quartz is fairly important, but it is clearly due to infiltration. Secondary calcite is also seen replacing large areas in some rocks.

The orthoclase is generally xenoblastic and crowded with inclusions due to its low crystalloblastic position. The soda felspar is clear, twinned, and at times approaches albite-oligoclase in composition. Veins of green epidote, distinctly younger than any of the minerals under review, are seen cutting through the hornfelses.

Petrographical Details.

Wollastonite varies in development and grain-size, but is generally strongly idioblastic in crystals pseudo-prismatic on "b", with a maximum length of 3 inches. Pinacoidal cleavages, marked multiple twinning, and evidence of general stability are the chief characteristics.

Grossular is generally xenoblastic and intimately associated with diopside, although dodecahedral crystals are infrequently found. The R.I. varies from 1·745–1·762, these figures indicating the presence of some of the andradite-molecule. The mineral is mostly colourless or pale-yellow, but becomes brown and more strongly refringent in certain areas. It is considered that such examples are really andradite, and their origin is discussed below.

Diopside is generally extremely xenoblastic, and is fairly rich in lime as $Z \wedge c$ is about 42°, and the D.R. is strong. In places a greenish tint indicates the presence of a proportion of hedenbergite-molecule. More strongly ferriferous types are encountered in some rocks and these are dealt with below. Alteration to fibrous actinolite is quite common, while in I.184 tremolite has developed. These products are doubtless partly due to some slight shearing-effect which the rocks in question have suffered.

Vesuvianite as a primary product of the metamorphism is not common in the assemblages. In one rock some partially kaolinized zoned crystals showing (100), (111), and (001) faces are to be seen, and in I.132 the vesuvianite is pale honey-yellow in colour, optically normal and negative in sign. From the details given in the next paragraph it will be seen that primary vesuvianite and that derived from grossular may occur in the same rock.

One of the most noticeable features in these rocks is the presence of vesuvianite or clinozoisite as derivatives from grossular. The two products do not occur together. The change may be traced with ease in certain rocks (e.g. I.125), and diablastic intergrowths of grossular and diopside pass by insensible gradations to diopside-vesuvianite or diopside-clinozoisite associations. The secondary vesuvianite has optical properties somewhat different from those of the thermal vesuvianite.

Some of the bands in the hornfelses consist almost entirely of pyroxene, and in many of these cases (e.g. I.99, I.104), the mineral shows abnormal interference colours, due to very pronounced dispersion, $\rho > \upsilon$. Peculiar bluish-violet and orange colours are seen, and the extinction-angles indicate the existence of an appreciable quantity of ferrous iron. It is also possible that the unusual dispersion is related to the presence of some other base. In some respects this variety of pyroxene recalls the mansjöite[1] of von Eckermann, which contains an appreciable quantity of TiO_2.

In the rocks of group 9 the pyroxene is not ferriferous as the maximum extinction, $Z \wedge c$ is 41°. The microcline is almost completely altered to sericite, the few remnants showing extremely fine twinning.

It remains to refer to the rocks in group 7. These are not common and are of interest because of the association of wollastonite with andesine. The latter shows a positive figure, and extinction-angle of 19° on (010), and is present in stumpy crystals set in plates of orthoclase, which also enclose the idioblastic diopside and wollastonite.

Textural Features.

Macroscopically many of the rocks present a striking appearance, large bladed crystals of wollastonite up to 3 inches in length and well-developed garnet being conspicuous, and producing handsome specimens. Apart from the contaminated and skarn-like rocks, the majority are light-coloured. Where, however, the grossular has been affected by iron-bearing solutions and made over into andradite, some characteristic rocks with dark streaks and patches have been produced. The general textures are diablastic and heteroblastic but in certain bands beautiful radiating fibrous structures occur. These are composed almost entirely of finger-like prisms of wollastonite, in between which perfectly isotropic and extremely small dodecahedra of grossular occur. The star-like clusters and spherulitic masses of wollastonite are often arranged in double rows, thus constituting veins in some hornfelses (see Pl. XII, Fig. 5). In these cases the bases of the stellate groups are arranged along the divisional planes between layers that originally were siliceous and argillaceous respectively. The crystals of wollastonite have grown inwards away from the junctions, as there was less energy needed to crystallize within the gritty layer with its somewhat coarser texture rather than in the direction of the more compact shaly limestone layer.

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[1] *Geol. Fören. Förh. Stockholm*, 1923, 335.

Another important feature of the rocks is the presence of zonal banding, due to original differences of composition. The banding may be linear or concentric, and the differences in the assemblages in the various layers show that diffusion during recrystallization has been very limited. The details of these structures will be discussed when the genesis of the rocks is being considered.

(3) *Rocks which have been affected by pneumatolytic action.*

In this category we have to consider some remarkable rocks which show striking textural characters, and by reason of their mineralogical constitution deserve some special notice. In some of these types the rare custerite and also monticellite occur. A preliminary notice of this occurrence has already been given.[1] It is most satisfactory to include under the above heading certain rocks in which pneumatolytic action may have played only a small part, but which pass within the limits of a single hand-specimen into intensely pneumatolysed types.

The rocks showing pneumatolytic effects were found just a chain or two to the south of the boundary of the Townland of Irish Grange, at a point about 450 feet above sea-level, and distant ⅓ mile west from Grange Cross (see map : locality (4)). Here, a shallow excavation made upon these rocks in connection with a search for mica has not revealed the igneous rock responsible for the pneumatolysis, but there is no doubt that a pegmatitic apophysis of the acid magma must underlie the metamorphic rocks at no great depth.

Ignoring the relict patches from the earlier metamorphism (see below), the rocks are all seen to be examples of silica-poor assemblages. They may be treated as follows :—

(*a*) *Rocks whose essential constituents are phlogopite, diopside, vesuvianite, pleonaste, and calcite.*

The majority in this group contain all five minerals in varying associations, but vesuvianite or phlogopite may be absent from some. When phlogopite is absent the rock would find its right place under heading 2 (c) above, but such a rock is so intimately associated with the pneumatolysed types that it is best dealt with here. The accessory minerals are apatite, grossular, perovskite, sphene, magnetite, and pyrite. The texture is very variable because of the occurrence of large crystals of phlogopite and calcite set in finer material which displays poikiloblastic vesuvianite with chadacrysts of spinel and diopside. Again, diopside and more commonly spinel, may be set in phlogopite plates. In fact there appears to exist an intimate association between spinel and the mica. The heteroblastic structure is generally manifested best where there are abrupt changes from silicate-assemblages to large cleavage-blocks of bluish twinned calcite. Again, some heavy dark rocks are composed of dominant spinel with tufts of phlogopite. Finally, there are some dense, spheroidally-banded rocks of a cream colour, intimately associated with the foregoing, which consist of vesuvianite and its decomposition products. The general textural characters just described also apply to the rocks dealt with under (*c*) below.

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[1] G. D. Osborne, GEOL. MAG., LXIX, 1932, 61.

The large phlogopite crystals provide excellent material for study. They are frequently elongated parallel to the "c" axis, when spindle-shaped units result from oscillations between M(221) and another pyramid-face in the vertical zones. At other times the mineral is tabular on (001) with strong development of (221), and a tendency to eliminate the (010) faces thereby. Cleavage is perfect, and the colour-scheme involves tints of palest brown with $Z > Y > X$. The axial plane is parallel to (010), and the axial angle varies but is always very low, the maximum value being $2E = 12°$, as determined on the microscope using Mallard's constant. The mineral has negative sign, and the R.Is. are $\alpha = 1{\cdot}552$, $\gamma = 1{\cdot}590$, $\rho = v$ approximately; $\Delta = {\cdot}038$. A chemical test showed the presence of fluorine.

Pleonaste is mostly subidioblastic, or else in irregular aggregates of half-formed crystals showing cubes and octahedra. The colour is darkest green, and the mineral is generally embedded in phlogopite, the inclusions being so numerous as to take up 80% of the area of the host-crystal (see Pl. XII, Fig. 1). The large crystals are often surrounded by very fresh calcite, free from inclusions. The significance of this relationship is dealt with below. The pleonaste is often intergrown with magnetite.

The stumpy, subidioblastic pyroxene, which is best described as diopside, shows some unusual features, and will need some further chemical investigation. It displays the peculiar dispersion seen in some of the pyroxene of the lime-silicate hornfelses, and possesses a distinctive pale yellowish-green colour in transmitted light. Cleavage is poorly developed; the D.R. is ·023, and the more highly dispersive units give striking interference figures which indicate $\rho > v$.

Vesuvianite is quite abundant in most rocks, and shows abnormal interference colours. The zoned crystals, which have nuclei of tiny inclusions, are very uniform in size, being about 0·4 mm. in diameter, and show the (111), (110), and (331) forms well developed. The mineral has altered to a brown-stained fibrous material. In some slides there are patches of diablastic diopside-grossular growths, in which the garnet is often replaced by vesuvianite distinct from that of the rock proper. It is fairly clear that these garnet-pyroxene areas with secondary vesuvianite are of earlier formation than the rest of the minerals in these assemblages.

Perovskite is confined to odd patches of ragged aggregates intimately associated with diopside. It has a violet colour, and a refringence distinctly higher than a liquid reading 1·81 (approx.).

The mineral is not completely isotropic and some areas show fine grating-structure, not quite like the usual twinning of perovskite, but probably some kind of twinning, nevertheless. The other accessories call for no remarks.

(*b*) *Altered vesuvianite-rock :* Locality (4).

It is convenient at this stage to refer briefly to certain yellowish-white masses of rock contiguous with the spinel-phlogopite rocks. These are excessively fine-grained, with occasional crystals of pyroxene, mica, or sphene visible. Although secondary processes have caused some re-arrangement in the rocks, it is clear that these masses were originally bands of hornfelses rich in vesuvianite. Under the microscope one sees a confused mass of fine-grained radial fibrous material, through which is scattered ragged custerite as described below. The birefringence is low, and extinction is parallel to the fibres. The material is not homogeneous and it is clear that here we are dealing with hydrous silicates of calcium and aluminium, similar to the alteration product described for the Marulan vesuvianite. Close inspection shows that in between the fibres there are myriads of the most diminutive grossular granules. These, it is believed, are a product of the decomposition. In certain patches in these rocks scapolite was found, and also a few diopside crystals passing over to tremolite.

(*c*) *Assemblages with custerite and monticellite :* Locality (4).

Under this heading come the most important of all the rocks. Some types are essentially similar to those described above under 2 (*a*) except that custerite may occur in the interstices between the vesuvianite or pyroxene, or as a selvedge to phlogopite crystals, or again as a margin to calcite areas. The custerite, however, plays a much more important rôle in certain coarsely-grained rocks which often contain monticellite. A brief account already given[1] has provided some information regarding the paragenetic features of these rocks. Thus custerite and monticellite occur together in some rocks, and the former may occur separately, but monticellite rarely occurs alone. The chief associates of the custerite are monticellite, phlogopite, apatite, vesuvianite, and calcite. In order to illustrate these rocks three examples may be described. I.180 (see Pl. XII, Fig. 2). Within a slice 0·5 mm. in diameter the following minerals occur : phlogopite, spinel, custerite, monticellite, calcite, vesuvianite, diopside, wollastonite, edenite, grossular, apatite, pyrites, and magnetite. Certain groupings of the minerals occur and constitute distinct paragenetic systems. Large individuals of custerite (see earlier note for properties) enwrap monticellite and phlogopite with its many inclusions of pleonaste. Occasional larger detached crystals of pleonaste are surrounded by a corona of calcite. In local patches custerite is interstitial between grossular-

[1] Geol. Mag., loc. cit.

diopdise-vesuvianite intergrowths, the last-named being always much altered. In other places assemblages of grossular, edenite, wollastonite, diopside, and vesuvianite occur, while elsewhere custerite is intimately associated with calcite. The edenite is prismatic with positive figure and elongation, and shows fairly good cleavage in the amphibole fashion, with characteristic cross-sections. The angle $Z \wedge c$ reaches 28° and the D.R. is about ·015. Calcite is found threading through the rock, and sometimes includes strings of hexagonal prisms of apatite. I.186 (see Pl. XII, Fig. 3). This rock is even more striking than I.180 on account of its textural characters. The constituent minerals are custerite, vesuvianite (three varieties), phlogopite, calcite, apatite, and diopside. The vesuvianite may occur as follows: (*a*) in simple tabular prisms 4 mm. long showing perfect rectangular sections due to the presence of m(110) and c(001), and the almost complete absence of pyramids. These units show an abnormal greenish-fawn interference-colour, negative figure and elongation, and strong (110) cleavage; (*b*) in patches of fibrous-radial material showing the former presence of crystals distinct in form from those just described; (*c*) in aggregates of crystals intergrown with calcite. A distinctive spindle-shaped habit is given to some of the crystals by the presence of a steep pyramid, probably the form (331). The vesuvianite in this category is optically normal, and at times shows tabular development perpendicular to "c". In addition to the (110) cleavage, a distinct parting parallel to (001) is sometimes present.

The phlogopite is a little darker than usual and the calcite shows very strong twinning with broad lamellae and slight strain-effects. Apatite in crystals up to 1 mm. length is segregated locally in the calcite, and is distinguished from the normal vesuvianite by slightly lower refraction. Custerite plays a distinctive rôle, mantling vesuvianite crystals and occupying areas between these and calcite grains. In places it is very irregular and almost grades into the calcite (see Pl. XII, Fig. 4). I.187 (Pl. XIII, Fig. 1). Altered vesuvianite, with characters already described, makes up 90% of the rock. Occasional crystals of phlogopite, spinel, and diopside also occur, but the general mesostasis, in which the vesuvianite is set, consists of extremely ragged aggregates of custerite and calcite. Here, as elsewhere, it is clear that these two minerals have a genetic connection.

GENERAL DISCUSSION INCLUDING GENESIS OF THE METAMORPHIC ROCKS.

(1) *Rocks showing no connection with pneumatolytic action.*

(*a*) *Forsterite-spinel-brucite marbles.*

Rocks of this general type have been described from many places and several authors[1] have discussed the genesis of the constituent minerals. It is only necessary here to affirm that the present rocks have not been affected by addition of magmatic material, having developed from the recrystallization of impure dolomites. They are rather interesting in that the three non-carbonate minerals effecting de-dolomitization are all present. The paragenesis forsterite-spinel-periclase-calcite shows that the amount of alumina present was not sufficient to use excess magnesia from the dissociated dolomite molecule to give abundant spinel. Edenite is absent and it would appear that the chief factors controlling its occurrence are the relative proportions of silica and alumina present, the activity of water, and the temperature.

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[1] See particularly C. E. Tilley, GEOL. MAG., LVII, 1920, 457–60, and F. H. Hatch, and R. H. Rastall, *Quart. Jour. Geol. Soc.*, lxvi, 1910, 507.

The perovskite is doubtless younger than the other non-carbonate minerals, although belonging to the general thermal period. It has developed from patches or layers in the dolomite which contained detrital rutile. In a more siliceous rock, sphene would have formed.

(*b*) *Calc-silicate and calc-magnesian-silicate rocks.*

(*i*) *General Aspects: Grades of metamorphism and diaphthoresis.* —It is instructive to notice the various grades of thermal metamorphism displayed by the characteristic mineral assemblages. These are best shown by the more calcareous rocks in which silicates are very subordinate. In rocks of fairly low grade, calcite and quartz have not combined, but in a succeeding grade the predominant silicate is clinozoisite in rocks with little magnesia, while hornblende accompanies the clinozoisite in rocks containing magnesia. In a still higher grade, grossular occurs in non-magnesian assemblages which have not yet developed wollastonite, and diopside accompanies the garnet in the more magnesian rocks, although clinozoisite is often present due to retrogressive metamorphism. The main calc-magnesian-silicate groups described above contain wollastonite as a characteristic constituent and thus are all of high-grade type.

We now pass on to consider the occurrence of certain minerals which, it is believed, have resulted from changes during retrogressive metamorphism, and we can thus examine the status of clinozoisite and vesuvianite in these rocks. It has been shown above that in certain relatively low-grade marbles perfect crystals of clinozoisite occur in a manner suggesting they are stable thermal products. Further, idioblastic vesuvianite is found in rocks of somewhat higher grade, and this mineral has developed as a thermal product during the advance of the metamorphism. In the latter rocks, and also in other cases, vesuvianite and clinozoisite may occur as derivatives of grossular, but it is clear that atmospheric weathering is not the cause of the change. Beautiful diablastic growths of diopside-grossular pass into similar growths of grossular-clinozoisite or grossular-vesuvianite. It is the view here that these silicates with the hydroxyl group were generated during retrogressive metamorphism with which was associated a change promoted by falling temperature, and occurring at pressures under which grossular was not stable. This change was assisted by the activity of solutions such as are ubiquitous during thermal metamorphism of rock-masses. A similar degradation of andradite-grossular garnet (rather than a pure grossular) to epidote is recorded from certain Adelie Land rocks.[1]

The fact that vesuvianite is commonly developed as a true thermal product must not be lost sight of. The data available concerning the various grades suggests that while this mineral may occur with grossular and wollastonite, it is also stable in a lower grade where these two minerals fail to develop. Such features are seen in the Marulan aureole. Where pneumatolytic metamorphism operates in an aureole, fluorine, if available, enters the constitution of vesuvianite, but it is suggested here that vesuvianite which is due entirely to diaphthoretic changes, as outlined above, will be fluorine-free.

The similarity in composition shown by grossular and vesuvianite has recently been emphasized in papers by F. Machatschki,[2] and by B. E. Warren and O. I. Modell.[3] The first author discussed the chemical relationships between these minerals and suggested a close relationship in crystal-structure. The latter two writers, by X-ray analysis, have confirmed this suggestion.

Zonal Structures.

The frequent banding and concentric arrangement of assemblages which differ, sometimes slightly and sometimes appreciably in composition, have been recorded above. The simple stratiform banding needs no discussion, but the cases of spheroidal zoning naturally lead one to inquire if the zones have arisen by reaction between magma and sedimentary xenolith. In numerous papers authors have given evidence of the development of zonal structures in xenoliths by diffusion of magmatic substances, but in the present instance no such evidence is forthcoming, and the structure is essentially of pre-metamorphic origin. These remarks do not apply to rocks of the district which show definite evidence of pneumatolysis or metasomatism.

The consideration of these structures has been based upon the premise that diffusion during metamorphism is limited, and their whole interest lies in their spheroidal form. One finds in certain blocks in the Barnavave Quarry the following types in a spheroidally-zoned mass :—

(*a*) Grossular-diopside
(*b*) Grossular-wollastonite
(*c*) Diopside-microcline (sericite)
(*d*) Green diopside with smallest amounts of calcite
(*e*) Wollastonite-grossular-diopside-calcite

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[1] C. E. Tilley, *Aust. Antarctic Exped.*, Sci. Repts. Series A, 231.

[2] *Cent. f. Min.*, vii, 1930, 284.

[3] *Zeit. f. Krist.*, lxxviii, 1931, 422.

The differences are chiefly due to variations in the amounts of silica, magnesia, and alumina present in the zones, while in some cases potash is important. The value of the ratio CaO/MgO varies a good deal throughout a complex concretionary structure, and plays an important part in the presence of impurities. The existence of K_2O indicates a local concentration of sericitic material, and on account of the spheroidal nature of the mass, this mica must be regarded as authigenic in origin. The almost pure pyroxenic layers have been derived from a gritty zone which was subjected to selective dolomitization.

Concretionary lenses and spheroids are not uncommon in impure limestones, and in these the alumina- and silica-content must vary greatly. When such bodies are subjected to differential dolomitization the conditions requisite for the production of zoned hornfelses would result. A case where pre-existing zones have been accentuated by metamorphism is that of certain structures in the Cambrian dolomitic limestones of Kilchrist, Skye, in which silica was the sole impurity.[1]

(*ii*) *General Genetic Considerations.*—In discussing the origin of the main groups of calc-magnesian-silicate rocks, it is justifiably assumed that magmatic material does not play any part, with perhaps the exception of a limited transfer of silica in some cases. In this way one would explain the presence of veins through the limestones, which, in addition to wollastonite contain granular quartz which has the appearance of introduced material.

Considering the hornfelses from the standpoint of some classificatory scheme one sees that they are nearly all restricted to the calcic end of the well-known Goldschmidt groups, thus lying within the limits of the triangle wollastonite-grossular-diopside of Tilley's ternary diagram.[2] In spite of this, however, there is a fair variety, because simple two-phase assemblages represented by points on the sides of this triangle are not uncommon at Barnavave. Although these two-component rocks are never important quantitatively, they are more than microscopic in their dimensions, and may form bands in a composite rock.

With the exception of one special case dealt with in the next paragraph, no further discussion of the chemistry of the hornfelses is necessary. Similar rocks have been dealt with elsewhere by the writer,[3] and it is sufficient to list the probable impurities responsible for the silicates as sericite, chlorite, kaolin, and quartz.

The wollastonite-andesine-diopside-orthoclase type is of special interest as it constitutes what is essentially an unstable assemblage. Studies of pyro-metamorphic assemblages show that at high temperatures wollastonite-anorthite is stable while the corresponding association at lower temperatures is grossular-quartz according to the equation $CaAl_2Si_2O_8 + 2CaSiO_3 = Ca_3Al_2Si_3O_{12} + SiO_2$. In other words the anorthite molecule, if present, tends to enter grossular at the temperatures characteristic of ordinary thermal metamorphism. Now in the present rocks the anorthite has not united with wollastonite to give garnet, but has joined with albite to give an intermediate plagioclase. Such a hornfels is really unstable but the absence of grossular in this case does not imply that the temperature was too high for its formation. Apparently the presence of albite is the determining factor, and thus the assemblage wollastonite-andesine can exist at a temperature lower than that necessary for stability of wollastonite-anorthite. These essentially unstable hornfelses are not common at Barnavave, and it is not yet absolutely clear whether magmatic influence may or may not have had something to do with their composition and genesis. It may be mentioned in passing that A. G. Hutchison found somewhat similar unstable hornfelses in the metamorphosed Deeside Limestone, the existence of which he put down to "relief of static pressure during the growth of the lime-silicate minerals". Such physical control could have had little to do with the Barnavave case.

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[1] A. Harker, *Mem. Geol. Surv. Great Britain*, 1904, 147.

[2] GEOL. MAG., LX, 1923, 411.

[3] GEOL. MAG., LXVIII, 1931, 306–9.

Many of the calc-magnesian-silicate rocks show the presence of some free calcite, or sometimes a little infiltrated quartz, but all must be classified as quartzless assemblages. There are also many cases where CO_2 has been completely eliminated and the rocks are constituted entirely of silicates (neglecting such items as iron-ores). Such features have been interpreted by some authors as evidence of the development of hornfelses by accession of magmatic silica. On the other hand, it would appear, that in a limestone with sufficient number of bases present forming components of a system, the allocation of lime, silica, and the other oxides to one another may produce a silicate-rock devoid of excess carbonate.

(c) *Silica-poor assemblages.*

Under this heading comes a group of rocks occurring at Grange Irish, of which the most typical example is a diopside-vesuvianite-spinel-calcite assemblage. This is not a common paragenesis among metamorphic rocks and it is evidently a special case of diopside-grossular-spinel-calcite, which has been discussed by C. E. Tilley[1] in dealing with the silica-poor hornfelses from calcareous sediments. Apparently the diopside is the oldest silicate in these rocks, and after it vesuvianite was formed until silica failed, and the excess alumina was fixed in spinel. The vesuvianite has not developed from grossular, being stable as regards metamorphic grade, but it has succumbed in many places to the intense pneumatolysis which produced the custerite-bearing rocks.

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[1] GEOL. MAG., LXII, 1925, 365.

The frequent occurrence of a corona of calcite mantling pleonaste (e.g. I.185) is due to the setting free of this carbonate as a consequence of the breaking-up of dolomite, when the spinel was formed.

(2) *Rocks showing pneumatolytic effects: custerite-monticellite types.*

Any discussion of the rocks with custerite, monticellite, phlogopite, and other less significant silicates must take account of the following outstanding features. (*a*) They are very coarse and variable in texture; (*b*) they show evidence of the pre-existence of normal assemblages before pneumatolysis; (*c*) the mineralogical constitution varies abruptly from place to place; (*d*) certain associations are unstable by reason of the minerals present and their relations.

The great variety among the minerals, often seen within the compass of one rock-slice, is eloquent testimony of the variable chemical composition of the original sediment, and of the selective action of the pneumatolytic agents; it is also a vivid manifestation of the limited diffusion operative during the metamorphism. It is clear that in those rocks which contain relict patches of calc-silicate hornfels, there have been different assemblage-types consisting of phases derived from different multi-component systems. Thus side by side we find representatives of the systems $CaO-Al_2O_3-SiO_2$ and $CaO-MgO-Al_2O_3-SiO_2$. In addition there are minerals which possess an alkali component or a volatile component.

In working out the genesis of the custerite the petrographical and textural characters given above should be recalled, and the reader is referred to these. The intimate association of vesuvianite, calcite, and custerite may again be emphasised. It is the view here that the custerite has been produced from rocks containing vesuvianite and other silicates set in a calcite mesostasis, by reaction between the calcite and gases derived from the magma. The particular agents involved have been silicon tetrafluoride and water-vapour, with the latter in excess. By combined action of chlorine, fluorine, and a gaseous compound of phosphorus upon calcite, apatite has developed in a manner similar to that of the custerite.

Ignoring the relict patches of normal hornfelses and the altered vesuvianite, we can consider more specifically the genetic relations of the monticellite-phlogopite-vesuvianite-custerite-spinel-calcite assemblages, taken as a whole. We can dismiss custerite from the discussion, as it has been treated above, and it should be remembered that vesuvianite is to be regarded as a substitute for grossular. The groups may then be satisfactorily considered by employing the diagram given by C. E. Tilley [1] in discussing contact-assemblages in general. Some of Niggli's remarks [2] upon hornfels-assemblages also bear upon the subject of the present discussion.

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[1] GEOL. MAG., LXII, 1925, 363–7.

[2] *Fortschritte der Mineralogie, etc.*, viii, 1923, 70.

The assemblage monticellite-vesuvianite-calcite which is prominent at Grange Irish lies within a triangular field forming part of a tetrahedral index-solid, developed from Tilley's diagram (loc. cit.). Where spinel enters the rocks we have assemblages which find their place within a tetrahedron whose corners are given by the minerals mentioned. This type of assemblage is the unstable equivalent of diopside-spinel-vesuvianite(grossular)-calcite, which has been shown to occur at Barnavave.

The assemblages as a whole belong to the system CaO-MgO-Al_2O_3-SiO_2. Where we have rocks rich in phlogopite, (and generally also in spinel) we find that limited diffusion has permitted the development of distinct parageneses, e.g. of phlogopite-spinel, and monticellite-vesuvianite-calcite. The former can be regarded as a two-phase group in the system MgO-Al_2O_3-SiO_2, with the presence of K_2O, (OH), and F as special components, and it is analogous (but not equivalent) to such a group as cordierite-spinel.

Thus, summarizing, monticellite represents a stage in the development of equilibrium, which if attained would have permitted the generation of diopside as the stable type (i.e. in the presence of sufficient silica). The direct association at Grange Irish of these monticellite-bearing rocks with forsterite-spinel marbles leads to the conclusion that they have been derived from forsterite-diopside-spinel-calcite assemblages by pneumatolysis which succeeded the thermal change.

It should be noticed that besides the addition to the limestone of H_2O, F, Cl, and P, there has been a pronounced accession of potash (phlogopite) and iron (spinel). The spinel in the forsterite-marbles is iron-free, in contrast with that of the other rocks. The absence of chondrodite from the Grange Irish rocks is remarkable,and it is probably related to the value of the ratio MgO/Al_2O_3 and the presence of potash. Under the conditions obtaining, phlogopite has developed in some force.

In conclusion it may be remarked that the abundance of volatiles, especially fluorine, in the apophyses responsible for the pneumatolysis at Barnavave, recalls the similar chemical feature of certain phases of the Mourne granites, and it is probable that both sets of rocks are co-magmatic.

(3) *Skarn-like modifications of the hornfelses.*

Some of the hornfelses have been affected by hydrothermal solutions genetically connected with a phase of the acid magma-fraction of the Barnavave region. In this way local modifications of the calcic rocks have arisen, and these are best designated "skarns". They are rarely in sufficient quantity to permit large specimens being collected which do not embrace some hornfels or hybrid rock.

The skarns are always marginal to igneous veins and evidence of replacement of excess calcite by iron-bearing minerals is available in the thin sections. The limited occurrence of skarn-like rocks is due partly to the restricted metasomatic action, and partly to the scarcity of excess calcite in the country rocks.

The chief minerals in these rocks are andradite, wollastonite, hedenbergitic pyroxene, excess silica, and/or calcite. Pyrites in small quantities is common in vein-like segregations of andradite, and magnetite is rare. Apart from the garnet-pyroxene skarns, some phases of the hornfelses in the vicinity of pegmatites show two special features related to metasomatic activity. These are (i) the occurrence of disseminated units of brown andradite and (ii) the presence of a greenish pyroxene possessing strong dispersion. The former mineral has been produced locally from grossular, as gradations can be traced, and the latter must owe some of its peculiar properties to obscure magmatic influence, since these characters are developed only in the neighbourhood of the igneous veins. The solutions which caused the metasomatism were active in respect of both ferrous and ferric iron and the relation of these solutions to the pegmatite magma-liquid is best discussed in the next section.

CONTAMINATED IGNEOUS ROCKS.

Pegmatites with wollastonite, andradite, and hedenbergite.

The aplitic and pegmatitic offshoots from the acid igneous rocks of the Barnavave district show contamination where they traverse the metamorphosed limestones. In the Barnavave quarry pegmatoid apophyses are more frequent than aplites, but the mineral content is about the same in each group. When unaffected by addition of calcareous material the veins consist of microperthite, albite-oligoclase, quartz, and accessory magnetite and pyrites. Sometimes a very small amount of altered biotite or hornblende is present. The veins are always narrow, never exceeding 3 ins., and generally being about 1 inch in width. Contamination of two related types occurs; that due to reaction of magma and normal hornfels, and that produced by interaction of magma and skarn. The occurrence of these two types is directly related to the amount of calcite available for reaction with the pegmatitic liquid. Just as skarns were developed only where the hornfelses had excess carbonate, so the contamination is pronounced in the neighbourhood of skarns for the same general reason. In the case of the reaction with hornfelses the igneous veins have developed zones of diopside on their margins, and occasional crystals of β-zoisite have been formed.

The second case is more important and rocks of extreme interest have been produced. These are very striking by reason of the presence of large wollastonite crystals exceeding 3 ins. in length, and perfectly idiomorphic black andradite and hedenbergite, together with considerable orthoclase and plagioclase. The general structure is pegmatoid and in most cases the dark minerals are set poikilitically within the orthoclase plates. The veins grade on either side through a zone rich in garnet and pyroxene and poor in felspar into the adjacent skarn, which often still contains excess carbonate (I.148).

Under the microscope the minerals present are wollastonite, andradite, hedenbergite, labradorite, orthoclase, sphene, apatite, magnetite, and pyrites. Rarely there is a little quartz which may be residual, or due to infiltration. A most important feature is the dual rôle played by wollastonite; one phase is relict from the skarns, and the other consists of primary pyrogenetic prisms, laths, and needles which have crystallized out early from the magma-liquid. The presence of the acicular wollastonite is very striking (see Pl. XIII, Fig. 2). The hedenbergite prisms have a vivid emerald green colour, being slightly zoned, and attain a maximum length of 5 mm. Cleavage is fairly prominent and the pleochroism is not strong; $X =$ yellowish green, $Y =$ brownish green, $Z =$ emerald green, $Z = Y > X$. The mineral is positive, $Z \wedge c$ is 45° (max.), and the R.Is. are $\alpha = 1{\cdot}723$, $\gamma = 1{\cdot}741$, D.R. $= {\cdot}018$. The FeO present was determined, the result being $19{\cdot}1\%$. This corresponds to the solid solution $He_{64}Di_{36}$. The andradite crystals showing dodecahedra and trapezohedra are often grouped in aggregates, and possess a brown colour similar to that of the melanite-garnet of alkalic igneous rocks. Qualitative chemical tests showed, however, that the percentage of TiO_2 present was almost negligible, and apparently the colour is due chiefly to iron. The R.I. is distinctly higher than $1{\cdot}81$. Plagioclase is in well-twinned crystals up to 7 mm. diam. which show partial alteration to confused aggregates. The R.Is. lie between $1{\cdot}556$ and $1{\cdot}565$, and the composition is Ab_1An_1, in contrast with that of the felspar of normal pegmatite. Large plates of non-perthitic orthoclase act as host-crystals to the dark constituents. Sphene is present in good crystals which show peculiar pleochroism: $X = Y > Z$, X and Y being greyish pink, and Z, bright brick-red. Apatite occurs in local patches, always as large skeleton-crystals intimately associated with calcite. Quartz, if present, is interstitial and without granophyric relations to orthoclase.

An analysis of a typical contaminated pegmatite (I.138), is given on p. 229. In calculating the mode it has been assumed that the Fe_2O_3 is confined to andradite and the MgO to hedenbergite.

The composition of the plagioclase in the mode is the same as that determined optically, and the composition of the pyroxene calculated from the analysis is approximately the same as that deduced from the value of FeO determined separately. In view of the data available of the composition of garnets from skarns (see Eskola, 1921 [1]), one notes the possibility that the Barnavave garnet may contain a certain amount of alumina and a very small amount of magnesia, and thus slight alterations in the percentages of anorthite and diopside in the mode would need to be made. These changes, however, would not upset the general accordance shown between the calculated compositions and those determined optically.

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[1] *Översikt av Finska Vetenskaps-Societetens Förhandlinger*, Bd. lxiii, 1920–21, Afd. A., No. 1.

The mode is as follows —

SiO_2	48·50
Al_2O_3	10·45
Fe_2O_3	5·47
FeO	2·73
MgO	1·25
CaO	24·05
Na_2O	1·81
K_2O	2·13
H_2O +	·45
H_2O −	·05
TiO_2	·90
P_2O_5	trace
CO_2	1·70
S	·22
	99·94

	Orthoclase	12·23
$Ab_{51}An_{49}$	Albite	15·20
	Anorthite	14·46
$He_{59}Di_{41}$	Diopside	6·69
	Hedenbergite	9·42
	Andradite	17·27
	Wollastonite	17·05
	Calcite	3·90
	Sphene	1·67
	Pyrites	·71
	Water	·50
	CaO (excess)	·50
		99·60

Contaminated pegmatite; Barnavave, near Carlingford. Anal. W. H. and F. Herdsman.

Coming now to the genesis of the mixed rocks one needs to recall the general sequence of events in the igneous action of the district. Basic magma was responsible for the production of the hornfelses, and acid veins were injected later on, with associated pneumatolysis and metasomatism on a small scale. The petrographical evidence shows that the skarns were not generated by the action of the basic magma, and also indicates that they were developed before (even if not very long before) the crystallization of the pegmatites. Equally clear is it that the skarns owe their origin to hydrothermal solutions and not to pneumatolysis, for skarns are absent from the localities where pneumatolytic types occur, and vice versa. Thus the origins of the skarns and of the contaminated pegmatites are intimately connected.

The most significant of the relations between the skarns and the pegmatites are as follow :—

(*a*) The skarn zones are always marginal to the igneous veins.

(*b*) In passing from skarn to igneous vein the minerals become separated from the main metasomatized mass by the incoming of orthoclase, and eventually are found embedded in the felspars of the pegmatites.

(*c*) The garnet and pyroxene, while generally xenomorphic in the skarns, become beautifully idiomorphic in the pegmatites.

We are thus brought to the consideration of the time of metasomatism in relation to the beginnings of solidification of the pegmatoid masses. There are two alternatives :—

(*a*) The skarns were produced by solutions genetically connected with magmatic activity earlier than that responsible for the injection of the pegmatites.

(*b*) The skarns were actually produced by the pegmatite liquid and later reacted with it.

The first explanation implies two periods of injection of acid magma-material in the Grange Irish district—both post-eucrite in age. No examination of the igneous rocks of the district sufficiently detailed to test this hypothesis has yet been made, and the absence of good field-evidence may prevent the reaching of a satisfactory solution. The second alternative implies that the skarns were the result of metasomatism of calcite by the pegmatite magma, and that the same magma later reacted with the excess calcite to produce the coarse mixed rocks described above. Since the veins are often only about 1 inch in width it seems impossible that small quantities of a magma that had reached the pegmatitic stage could remain mobile sufficiently long for the metasomatism, and subsequent digestion of skarn-material, and finally for the coarse crystallization of idiomorphic minerals. Further, the solutions for the replacement of calcite would, in the normal case, arise at the close, and not at the beginning of the crystallization of the pegmatite. Thus one rejects the second hypothesis and relegates the formation of the skarns to a time anterior to the injection of the pegmatite liquid. The metasomatizing solutions came along the same fissures as those later filled by acid magma. This view is to some extent supported by the complete absence of skarns from some carbonate-bearing hornfelses which are in contact with pegmatite.

Since the above was written the writer has been able to see Eskola's interesting paper[1] upon the sviatoinossites and other rocks of Sviatoy Noss, Russia, and a brief reference to it is pertinent. The mode of occurrence of the sviatoinossites and their relations to andradite-skarns are practically identical with those described for the Barnavave occurrences. The sviatoinossites are interpreted as being due to the addition of lime to a syenite magma, which has produced skarns and later reacted with its own " metasomatic contact product ". The interpretation given for the Barnavave occurrence differs from that of Eskola in that the same magma-liquid is not called upon both to produce and later resorb the skarns.

The contamination can now be considered in greater detail. Much has been written in recent years regarding contamination of magmas by sediments, and the reciprocal reaction between non-calcareous rocks and magmas has been more fully investigated than the cases where calcareous types are involved. In the latter cases the process is somewhat different from that of the former, because in the reaction with calcite CO_2 is expelled, and this gas really constitutes a component in the phase-assemblage of the country rock. This elimination of CO_2 upsets the mechanism of reciprocal reaction as operative in other cases. Sometimes the changes amount to an intense metasomatism of the limestone by the magma, as described by C. E. Tilley for the remarkable contact at Scawt Hill.[2]

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[1] Loc. cit., *supra*.

[2] *Min. Mag.*, xxii, 1931, 431–68.

Many authors have described examples of reaction between acid magma and calcareous wall-rock where there has been an addition of constituents to the igneous mass and a transfer of other constituents to the limestone, but there are also examples like the present case where lime has been incorporated by the magma, and practically no material has gone into the sediment. The absence of transfer of potash from the pegmatites to the hornfelses of the Barnavave quarry is perhaps the most outstanding feature of the Barnavave case.

H. H. Read [1] has recorded an interesting association of diopside-skarn and lime-enriched pegmatite from the Ellon district in Aberdeenshire, which he interprets as an example of reciprocal reaction in the sense defined by him in connection with the contamination of the Arnage gabbros. While the present writer does not know the Ellon occurrence, he would suggest that in certain cases where skarn and contaminated igneous rock occur in close association (as at Marulan and Carlingford), the mechanism helping to produce these relations has not been exactly of the nature of the reciprocal action described by Read for the contamination of gabbro by shale. In the latter case there has been an ordered, simultaneous, two-way migration of ingredients, whereas in the other examples cited, it would appear that the incorporation of lime and the crystallization of the igneous rock may precede the activity of the residual watery solutions bearing silica and iron, which have wrought metasomatic effects at the extreme late-magmatic stage.

Thus from the microscopical and field evidence we conclude that the pegmatites reacted with the excess calcite in the skarns taking CaO into solution, and from the lime-enriched magma prisms and needles of wollastonite, and subordinate crystals of sphene began to crystallize. The albite molecule joined with available lime to produce labradorite, and the orthoclase eventually crystallized free from perthitic intergrowth. Along the margins of the veins mechanical action of the liquid helped to separate the garnet and pyroxene from the skarns, and under the influence of the magma these minerals recrystallized in much the same way as minerals recrystallize during metamorphism, i.e. in the presence of a solvent which does not dissolve them bodily. Thus by gradual solution in certain places and crystallization in regions of least pressure, idiomorphic boundaries replaced the irregular outlines of the garnet and pyroxene, and these minerals came to be set in orthoclase oikocrysts. The temperature at first must have been fairly high as we find the pyrogenetic wollastonite stable, but there was not sufficient superheat to permit of more than the lime being incorporated by the pegmatite. Conditions of low viscosity in the pegmatites must have been maintained for some time (possibly partly by the action of the expelled CO_2), so as to allow the growth of large crystals and the penetration of the skarn-zones by magma-liquid, especially that rich in the orthoclase molecule.

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[1] *Trans. Edinburgh Geol. Soc.*, **xi**, 1925, 353–6.

The presence of well-formed wollastonite, andradite, and hedenbergite raises the question of their stability in an acid or intermediate calcic magma. When a magma comes into contact with xenolithic minerals which stand higher in a reaction-series than the phase with which the magma is saturated, the magma endeavours by reaction to convert such xenocrysts into phases with which it is saturated and thus establish equilibrium within itself. In the present case, after the escape of CO_2, there was little time for reaction, and crystallization proceeded with falling temperature, although pyrogenetic wollastonite was able to form. The darker minerals have not been attacked and thus appear stable. It is probable, however, that in larger masses of magma the andradite would be altered, but possibly the hedenbergite would remain stable, just as lime-rich diopside is in sub-acid magmas. The melanite of alkalic igneous rocks is certainly stable in magmas of a fairly wide range of composition, but its chemical composition is distinctly different from that of the andradites of skarns, by reason of the presence of a not inconsiderable quantity of TiO_2.

ACKNOWLEDGMENTS.

In connection with the general aspects of this research the author has received useful advice from Professor O. T. Jones, and in the particular problems of the work has been helped by discussion with Dr. A. Harker and Professor C. E. Tilley. He is also indebted to the latter for valuable assistance in dealing with petrographical difficulties, and is grateful to Dr. R. H. Rastall for kindly consenting to read the proofs of this paper. Finally, he acknowledges financial assistance from the Department of Scientific and Industrial Research, London.

EXPLANATION OF PLATES XII AND XIII.

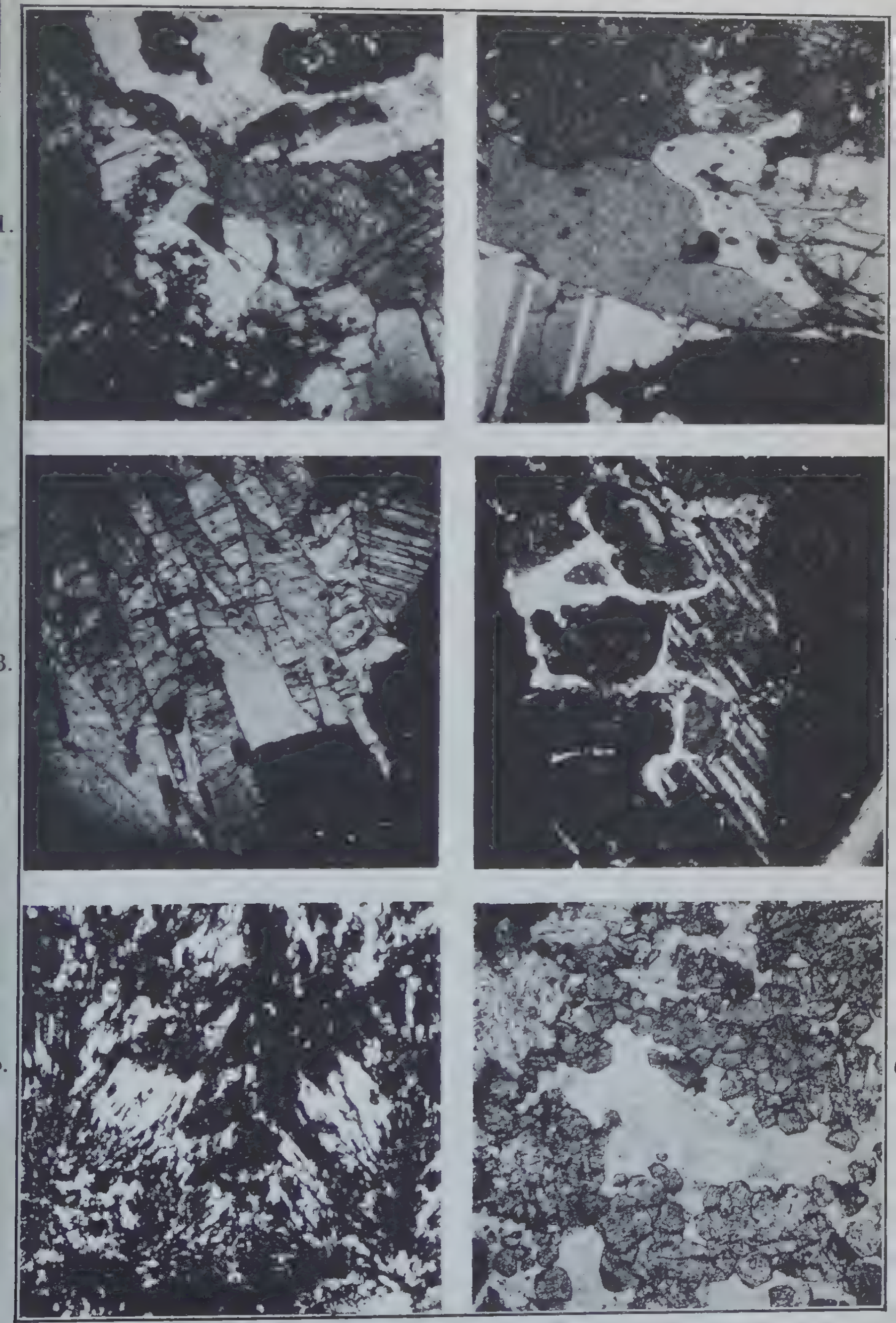
PLATE XII.

FIG.

1.—Metamorphosed limestone; Grange Irish. Phlogopite-spinel assemblages occupy the lower part of the photograph, and there is a crescentic band of custerite in the upper portion. This includes dark patches of altered vesuvianite, and shows broad twin-bands towards the right of the crescent. Small units of diopside occur between the custerite and phlogopite, and the rest of the rock is calcite. Crossed Nicols, × 8 diameters. I.189.

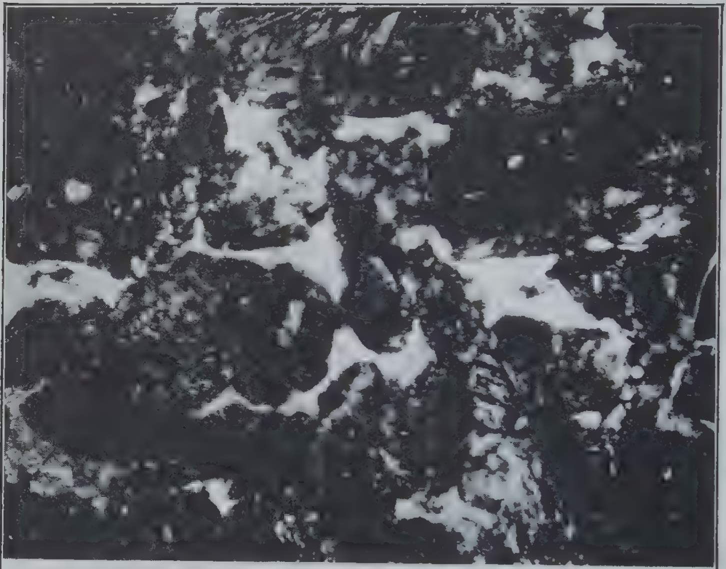
2.—Metamorphosed limestone; Grange Irish. Custerite with pronounced twinning shown in left-hand corner, and on right-hand side just above centre. Calcite in left portion of figure (containing apatite crystals), with monticellite and custerite to the right, and altered vesuvianite above. Crossed Nicols, × 16 diameters. I.180.

3.—Metamorphosed limestone; Grange Irish. Vesuvianite of two varieties: (*a*) In optically normal crystal-aggregates set in calcite; (*b*) in simple rectangular prisms showing alteration and optical anomalies. The dark character of the second type is due to the polarization colour being yellowish-fawn. Crossed Nicols, × 8 diameters. I.186.

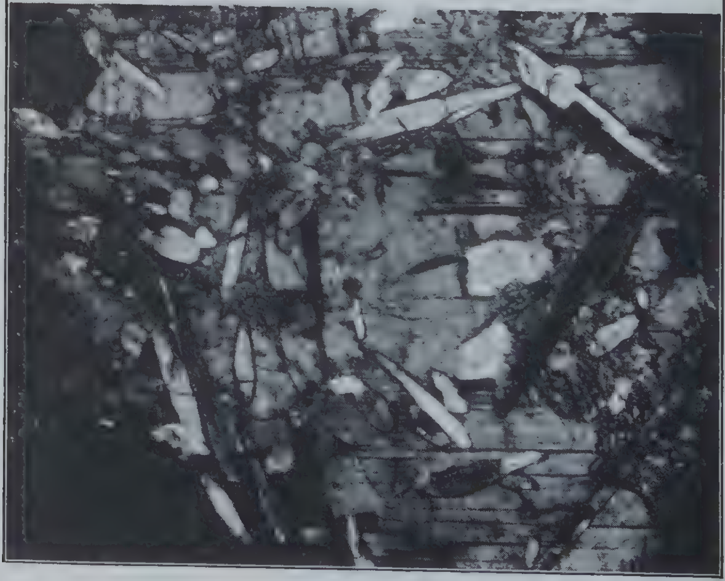


PHOTOMICROGRAPHS OF ALTERED LIMESTONES AND CONTAMINATED PEGMATITE FROM CARLINGFORD DISTRICT.

1.



2.



PHOTOMICROGRAPHS OF CUSTERITE-ROCK AND CONTAMINATED PEGMATITE FROM CARLINGFORD DISTRICT.

To face p. 233.]

FIG.

4.—Metamorphosed limestone; Grange Irish. Ragged custerite (white), mantling intensely altered vesuvianite crystals, and associated with calcite showing broad twin-lamellae. Dark mass to the left is also altered vesuvianite. Crossed Nicols, × 16 diameters. I.186.

5.—Wollastonite-grossular hornfels; Barnavave Quarry. Typical of certain zones in banded hornfelses. Radial groups of wollastonite, subordinate grossular, and a little quartz. The bases of the stellate groups can be seen against the line of quartz grains (at extinction) near the bottom of the figure. Crossed Nicols, × 59 diameters. I. 123.

6.—Contaminated pegmatite: Barnavave Quarry. Idiomorphic andradite and associated hedenbergite (darker units), together with odd crystal of wollastonite (at centre of figure); all these constituents are set within partially altered orthoclase. Ordinary light, × 16 diameters. I.148.

PLATE XIII.

1.—Vesuvianite-custerite-calcite rock; Grange Irish. Extremely xenomorphic custerite has developed from the calcite mesostasis between vesuvianite crystals, which are now changed to fibrous decomposition-products. Crossed Nicols, × 22 diameters. I.187.

2.—Contaminated pegmatite; Barnavave Quarry. Laths and acicular crystals of wollastonite, and dark hedenbergite (left side) are set in labradorite. Crossed Nicols, × 22 diameters. I.138.

A Bibliography of the Tectonics of England and Wales.

By R. H. RASTALL, M.A., Sc.D., F.G.S.

FOR more than twenty-five years the compiler of this bibliography has been deeply interested in the tectonic history of the British Isles: for the greater part of this time he has also been struck by the absence of any adequate and annotated treatment of the subject, since the appearance of the third edition of Jukes-Browne's *Building of the British Isles*, 1911. (The so-called 4th edition of this work, dated 1922, appears to be merely an unrevised reprint of the 3rd edition.) In 1929 this want was in part supplied by the publication of *The Physiographical Evolution of Britain*, by Dr. L. J. Wills. Even in this admirable work, however, the stress is on physiography rather than on tectonics, and many of the more important writings on this side of the subject are not referred to. In the *Handbook of the Geology of Great Britain*, which appeared in the same year, the exiguous section on "Morphology" includes no bibliography, while the whole scheme of treatment is in the main palaeontological, and little help on the tectonic aspect is to be obtained from the text of most of the sections. The present publication may in a sense be regarded as a supplement to that work.

A private collection of references has been sifted, amplified, and brought as far as possible up-to-date as regards England and Wales, and is here published in the hope that it may be of use to others. The literature of Scottish tectonic geology is so large and so much better known that it is not here included.

Naturally no references are given to general textbooks of geology, and with a few special exceptions the publications of the Geological Survey are not listed, as they are, or ought to be, well known to everybody. A small number of foreign memoirs are quoted when they have a special bearing on the less well-known features of British geology. Some of these, as well as many of the English works quoted, themselves contain valuable bibliographies.

The actual references are made as short as possible, giving only name of author, title, and date in the case of a book; for a single paper in a journal, name of author, title (occasionally shortened), volume number, date, and page. It may be noted that for a few years from 1915 onwards there is so much confusion in the dates of the volumes of the *Quarterly Journal of the Geological Society* that the figure given on the title-page is only misleading: such figures are omitted, and only the volume number, which *is* reliable, is given. The discrepancy between the years quoted on the title pages and on the backs of the unbound parts of this and other publications has wasted many hours of the writer's time in his editorial capacity, and affords a striking example of the unfortunate effects of a pedantic adherence to bibliographical exactitude.

It is not proposed to distribute separate copies of this bibliography in the usual way, but the author has had some reprints made, which he will be pleased to send on application to any one interested in the subject.

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REVIEW.

MICROSCOPIC DETERMINATION OF THE ORE MINERALS. By M. N. SHORT. pp. vii + 204, 11 plates, 16 text-figures. United States Geological Survey, Bulletin 825. Washington, 1931. Price, 60 cents, paper covers.

THE appearance of this bulletin is a welcome event to all petrologists interested in the microscopy of the opaque ore minerals. It presents the considered views of the author after several years' practical work at Harvard and on the Survey. Parts I and II describe the metallographic microscope, the technique of preparing polished specimens, photomicrography, and the investigation of physical properties—colour, hardness, and optical properties. The merits of black magnetic rouge in place of magnesia in certain cases for polishing are urged; the simplicity of practical photomicrography forms the basis for a plea for extensive recording of results in this manner; for colour-comparison, a double microscope is preferred to any indirect method.

The general impression conveyed by these first two parts is that no apparatus or method is described unless the author has convinced himself experimentally of its practical utility, and any criticisms offered by the reviewer are therefore rather an expression of personal opinion. The levelling cup seems a much more clumsy device than a hand-press of the type in universal use in Europe; square brass tubes for the permanent mounting of specimens have several disadvantages compared with a plug of suitable cement removed from the containing wall when set. The statements on p. 7 that "for ordinary work . . . daylight furnishes satisfactory illumination" and that an "oil-immersion lens [is] occasionally used" can be reconciled with practice only on the assumption that the bulletin is written primarily for those interested in the geological relationships of ore minerals rather than in their detailed mineralogical characteristics. The same reason also probably accounts for lack of reference in the section on optics to the measurement of reflecting power as a diagnostic criterion.

One is glad to find Part III, which includes the actual determinative tables, opening with an appeal for strict adherence to the European usages of the terms "etch-test" and "microchemical test". (It may be remarked in parenthesis that a similar confusion is still apparent in the use of the awkward term reflection-*pleochroism* for changes of *intensity* of reflected light, p. 44.) The determinative tables use successively the effect on polarized light, the hardness and systematic etch-reactions, confirmation being secured by qualitative microchemical tests. A single division into "hard" and "soft" is wisely preferred to further subdivision, and no diagnostic use is made of variable phenomena such as the character of the etched surface after rubbing.

The account of microchemical methods constituting Part IV, and occupying 90 pages, is the author's most valuable and original contribution to an already valuable bulletin. The use of such methods is advocated on the score of very great saving of both time and material, and special attention has been given to the determination of the sensitivity of each test proposed, and of the extent to which the presence of other elements interferes with a test for one particular element. After an account of the technique, the selected tests are listed in detail under particular elements. An outline of a systematic scheme of analysis follows, and in conclusion specific confirmatory tests for 159 minerals arranged in alphabetical order. Ten excellent plates, largely in colour, illustrate the results of typical tests. The index could easily be considerably improved.

To summarize, Professor Short's bulletin will assuredly take a well-merited place beside Bulletin 679 as a standard work on determinative mineralogy.

F. Coles Phillips.

REPORTS AND PROCEEDINGS.

Edinburgh Geological Society.

18th November, 1931.

"The Glaciation of Moray and Ice-Movements in Northern Scotland." By Alex. Bremner, M.A., D.Sc.

It has already been shown that during the Ice Age there have been in Banffshire and Aberdeenshire three separate ice-movements and probably three separate ice-sheets. The first came from west and north-west, the second from south and south-west, and the third, which did not everywhere reach the east coast of Aberdeen and Kincardine, travelled from the west and north-west in northern Banff and Aberdeen, from the west in Southern Aberdeen and Kincardine.

The purpose of the lecture was to show that a similar succession of ice-movements can be distinguished in Moray, that term being used as embracing roughly the ancient province of Moravia—the basins of the lower Nairn, Findhorn, Lossie, and lower Spey.

The different movements are proved by study of (1) the direction of striae engraved on solid rock, (2) the carry of erratics, (3) the stratigraphical relations of the boulder-clays left by successive ice-sheets, and (4) the direction of overflow channels cut by meltwater issuing from the latest ice-sheet during its recession.

The striae impressed during the first and third movements run in Moray in much the same directions; and, where there is no cross-striation, it is frequently impossible to distinguish one set from the other. In certain districts, also, the motion of the second ice-sheet was in a direction almost—and sometimes even exactly—opposite to that of the first and third ice-sheets. Other criteria, however, leave one in no doubt as to the directions of movement at different periods. Especially instructive is the fine section on the east bank of the Spey opposite Rothes. Here on Sandy Hill three boulder-clays are clearly exposed—the first and lowest brought by ice from the north-west, the second by ice moving down the Spey valley, and the uppermost by ice again travelling from the north-west. The suite of erratics from the lowest is almost identical, stone for stone, with that from the uppermost.

There is strong evidence that the first ice-sheet crossed the Moray Firth bringing erratics from Ross and Sutherland, and invaded Moray and the districts further east. During the second or northerly movement the ice descended to, and passed far beyond, the south shore of the Moray Firth.

The first ice-sheet of Moray was part of a great *mer de glace* that has left traces of its southward movement in the shape of erratics and southwardly directed striae almost as far as the Firth of Tay.

In Caithness the ground moraine of this early ice-sheet is represented, so far as we know at present, only by the boulder-clay found in the lower part of the bores at Leavad.

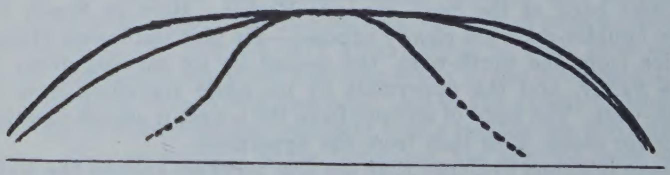
The second ice-sheet of Moray took part in the great movement that passed north-west over Caithness and the Orkneys, covering the former with dark boulder-clay charged with fragments of shells and of Jurassic and Cretaceous rocks mainly dredged from the bed of the Moray Firth: to the latter it carried in a brown moraine Carboniferous rocks from Fife, tuffs from the Ochils, schists and basic igneous rocks from Banffshire and Aberdeenshire. It also flooded the coastal districts from Stonehaven to beyond Peterhead with red Strathmore Drift.

The third ice-sheet, far less extensive than its predecessors, was responsible for the numerous and striking overflow channels cut by meltwater during its recession. These clean-cut channels head up northward towards the south shore of the Moray Firth, and then westward and south-westward towards the Great Glen. In Caithness the equivalents in time of this latest ice-sheet were considerable glaciers, one of which extended as far as the shores of Sinclair Bay, and the ice-caps that enveloped comparatively low hills beyond the limits of the glaciers; in Orkney and Shetland spreads of loose drift are due to a partial glaciation of the islands at this time.

CORRESPONDENCE.

THE PUY GRAND SARCOUY.

Sir,—Poulett Scrope's classic *Geology and Extinct Volcanos of Central France* contains a number of graphic sketches which are not drawn to scale and do not give a true picture of the forms of the puys. The drawing of the trachyte flow of the Grand Sarcouy reproduced in Scrope's *Volcanos*, 1872, p. 133, is a case in point, and, as this is misleading some authors, it may be well to point out that the puy is flat-topped with steep convex sides. In the diagram the middle curve represents the profile of Sarcouy seen from the south-west, and the outer curve the profile seen from the Gergovia Plateau to the south-east. The inner curve is the outline of Scrope's illustration.



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